International Telecommunication Union

ITU-R

Radiocommunication Sector of ITU

Report ITU-R TF.2511-0

(10/2022)

Content and structure of time signals to be disseminated by radiocommunication systems and various aspects of current and potential future reference time scales, including their impacts and applications in radiocommunication

TF Series

Time signals and frequency standards emissions

International Telecommunication Union

Foreword

The role of the Radiocommunication Sector is to ensure the rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including satellite services, and carry out studies without limit of frequency range on the basis of which Recommendations are adopted.

The regulatory and policy functions of the Radiocommunication Sector are performed by World and Regional Radiocommunication Conferences and Radiocommunication Assemblies supported by Study Groups.

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ITU-R policy on IPR is described in the Common Patent Policy for ITU-T/ITU-R/ISO/IEC referenced in Resolution ITU-R 1. Forms to be used for the submission of patent statements and licensing declarations by patent holders are available from http://www.itu.int/ITU-R/go/patents/en where the Guidelines for Implementation of the Common Patent Policy for ITU-T/ITU-R/ISO/IEC and the ITU-R patent information database can also be found.

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SM	Spectrum management
TF	**Time signals and frequency standards emissions**

***Note**: This ITU-R Report was approved in English by the Study Group under the procedure detailed in Resolution ITU-R 1.*

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REPORT ITU-R TF.2511-0

Content and structure of time signals to be disseminated by radiocommunication systems and various aspects of current and potential future reference time scales, including their impacts and applications in radiocommunication

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Scope

In response to *resolves to invite the ITU Radiocommunication Sector* 4 of Resolution **655 (WRC-15)**, in the framework of ITU-R that Report was developed to address information regarding content and structure of time signals to be disseminated by radiocommunication systems and various aspects of current and potential future reference time scales, including their impacts and applications in radiocommunication.

Keywords

Standard frequency and time signal, Coordinated Universal Time, Reference time scale, Dissemination of time signals, Radiocommunication systems

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1 Introduction

This Report responds to Resolution **655 (WRC-15)** and Question ITU-R 236-2/7. It is intended to inform the administrations and Sector Members of ITU as well as a wide audience of telecommunication companies, internet providers, space agencies, aviation, maritime and meteorological organizations, universities and authorities, providing them with an understanding of regulatory, technical and practical aspects of time keeping and dissemination of standard frequency and time signals. The following topics are covered in this Report:

- the role of the various organizations having responsibilities for the definition, maintenance, realization and dissemination of Coordinated Universal Time (UTC);
- background on the origins of UTC and the importance of using UTC for different applications, including new technologies (navigation, telecommunications, networks, and civil time keeping), and the impact of leap second insertions;
- the description of current and potential future time scales, including technical issues related to the future of UTC;
- the dissemination of time signals via radiocommunication systems;
- the use of UTC in radiocommunication services, technology, science and other applications;
- the impact of using UTC in radiocommunication services, technology, science and other applications.

2 Background

With the aim of providing technical background necessary to consider time scale issues, this section provides a summary of previous studies by the ITU-R and other relevant organizations to the evolution and possible future development of international time scales.

2.1 The origins of UTC

The rotation of the Earth has been used since antiquity as a means of measuring time. The irregularities in the rotation of the Earth resulted in increasingly more complicated versions of rotational time scales to attempt to produce a uniform time scale. In this effort the short-lived, dynamical Ephemeris Time based on the yearly revolution of the Earth around the Sun was even used. Eventually these attempts resulted in the change from astronomical time to atomic time scales. In 1967, the second of the International System of Units (SI, *Système international d'unités*) was redefined from a fraction of a year to an interval of time based on the radiation obtained from a specific energy level transition in the Caesium 133 atom. The measurement of that frequency in the years 1956 to 1958 in terms of the Ephemeris second resulted in the adoption of the duration of a second equivalent to the duration 1/86 400 of a mean solar day in 1820. International Atomic Time (TAI) based on this redefined second was introduced as a continuous metrological reference time scale in 1970 and is thus independent of the irregularities of the Earth's rotation.

Celestial navigation at that time was still a primary means of navigation at sea, and this technique required knowledge of the Earth's rotation angle. An error of 1 second in time translated into an angle, results in an error of ±0.4 km in longitude at the equator. To accommodate this need, UTC was created officially in 1962 (IERS EOP 14 C04 (1962-now) and Guinot and Arias, 2005) and adjusted in both epoch and frequency to attempt to match the Earth's rotation angle measured as Universal Time 1 (UT1), leading to UTC seconds that were variable in duration. The present realization of UTC as a stepped atomic time scale was adopted in concept in 1970. It was reported in Recommendation ITU-R TF.460 – Standard frequency and time signal emissions (current version 6 from 2002), and came into practice in 1972. The time offset steps are known as leap seconds and are introduced in UTC when necessary to limit the difference between UTC and UT1 within 0.9 second. The offset between UTC and UT1 is determined by the International Earth Rotation and Reference Systems Service (IERS) which announces, when needed, the insertion of a leap second in UTC. The realization of UTC is made by the BIPM from data provided by timing centres as described in Panfilo and Arias, 2019.

UTC is based on the continuous atomic time scale TAI that, on average, runs faster than UT1. This is a result of the atomic second being approximately equal to the rotational second of the mean solar day of the 1820 epoch. Since then, the rotation velocity of the Earth has gradually slowed down (mainly because of the tidal friction and also due to glacial isostatic adjustment along with irregular variations caused by movements of mass within the Earth), so that the average second of the contemporary length of day is slightly longer than the TAI second. In turn, TAI presents an increasing advance with respect to UT1.

Over the last fifty years, the UT1 second has been 2×10^{-8} s longer than the SI second on average, causing about 37 seconds difference between TAI and UT1 in 2020, 27 seconds difference of them inserted since the adoption of the present UTC system in 1972. The introduction of leap seconds is irregular, for a part of it is conditioned by the decadal fluctuations of the rotation velocity. When the Earth's rotation accelerates, the UT1 second approaches the SI second, even becoming shorter. Then the negative drift of UT1 with respect to TAI is not only stopped but becomes positive. Whereas the decadal acceleration strongly delays the introduction of leap seconds (as over the periods 1999 to 2006 and 2017 to at least mid-2023), until now it has never compensated the additional seconds inserted in UTC. Nevertheless, the rate of the Earth's rotation is expected to continue its secular deceleration so that, in the future, more than one leap second per year would be needed.

The moment of the adoption of a formal resolution on the definition of TAI and UTC by the *Conférence générale des poids et mesures* (CGPM) deserves a historical introduction. The CGPM in the 1960s – 1970s was responsible for making decisions on the SI, and the *Bureau international des poids et mesures* (BIPM) was responsible for the technical issues related to the dissemination of the units. The *Bureau international de l'heure* (BIH), operated by the *Observatoire de Paris* with the support of the scientific unions, had been charged with the maintenance of the time scales, first with that related to the Earth's rotation angle, and since the 1970s with the atomic time scales TAI and UTC. In 1988 arrangements were made to move the responsibility for the international reference time scales to the BIPM, with the logical consequence of making the same organization responsible for the unit of time and the associated time scales. In consequence, while the SI second was defined by the CGPM in 1968, TAI was defined in 1970 only by the *Comité international des poids et mesures* (CIPM), following a recommendation of the *Comité consultatif pour la définition de la seconde* (CCDS) (Terrien, 1971); in 1975 UTC, already in use, was endorsed by the CGPM (Terrien, 1975). The CGPM requested the CIPM to give a definition of TAI in 1971 (Resolution 1 of the 14th CGPM, Terrien, 1972), however, for these historical reasons the request was not immediately fulfilled, and the formal definitions of TAI and UTC were adopted by the CGPM only quite recently in 2018.

A set of documents (resolutions, recommendations and scientific publications) issued by the different organizations give the full description of UTC. The definition of UTC is given in Resolution 2 of the 26th CGPM 2018 "On the definition of time scales" (see Annex 1), and in the related documents of the CIPM and the *Comité consultatif du temps et des fréquences* (CCTF), basing the international timekeeping on the SI unit. The process to keep synchronization of UTC with UT1 is described in Recommendation ITU-R TF.460.

The implementation of UTC was well adapted to the applications and technologies existing in the early 1970s, and so this unique reference for time dissemination represented a good compromise for all users. However, since the late 1980s electronic navigation systems have significantly replaced celestial navigation. Some systems have even established continuous operational internal system times.

With more than four decades of experience with UTC being a stepped atomic time scale, the procedures for inserting leap seconds have been established and refined. However, with the emergence of ever-more sophisticated equipment, systems and services, these procedures could introduce ambiguities in dating and coordinating events. In addition to radio broadcast time services dedicated to disseminating accurate time by synchronized time codes to a variety of users, accurate time is now disseminated by terrestrial and space navigation systems, through computer networks, telecommunication networks, and the variety of other systems that they serve. UTC provides the reference for many applications in time synchronization at all levels of precision, from minutes needed by the general public to nanoseconds required by an increasing number of demanding applications.

The case of global navigation satellite systems (GNSS) is typical. The internal system time of the United States Global Positioning System (GPS), known as GPS Time, is a continuous measurement reference for the system's precise ranging capability. It is kept in a close relationship with UTC(USNO) as maintained by the United States Naval Observatory (USNO), modulo an integer number of seconds. GPS Time is an independent continuous time determined by the system's own atomic clocks that are corrected with comparative data from USNO to provide a time scale related to UTC. This system time is then easily available at all levels of precision from a second to a few nanoseconds.

Similar features have been adopted for the European Galileo satellite navigation system and the Chinese satellite navigation system known as BeiDou.

The system time of the Russian radionavigation satellite system GLONASS follows the Russian national time scale UTC(SU) + 3 hours. GLONASS system time is corrected by leap second insertions simultaneously with the UTC(SU) adjustment as announced by the IERS and as described in Recommendation ITU-R TF.460.

The GLONASS system time scale with a constant three-hour offset is maintained within ±8 ns in relation to the Russian national time scale UTC(SU) and less than ±1 s in relation to Universal Time UT1. The information with respect to deviation of the GLONASS system time scale from UTC(SU) and deviation of UTC from UT1 is transmitted to the users by the corresponding corrections in the satellite navigation signal. (GLONASS Interface Control Document (Ed: 5.1), 2008.)

2.2 Organizations with responsibilities related to UTC

UTC has been adopted by most countries as their basis for legal time, and is, in most of the world, the standard time adjusted for time zones. UTC as the international reference time scale is considered in a variety of standards and recommendations throughout the metrology and radiocommunication communities.

2.2.1 International Telecommunication Union

Founded in 1865 to facilitate international connectivity in communications networks, the International Telecommunication Union (ITU) with its headquarters in Geneva is the oldest international scientific-technical organization of the United Nations specialized agencies for all telecommunications.

The mission of the ITU Radiocommunication Sector is, *inter alia*, to ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including those using satellite orbits, and to carry out studies and adopt recommendations on radiocommunication matters. Historically, the "International Radio Consultative Committee" or "Comité consultatif international pour la radio" (CCIR) was founded in 1927 as part of the International Telecommunication Union at the International Radiotelegraph Convention of Washington, 1927. Only in 1992, the CCIR was merged into the Radiocommunication Sector (ITU-R), as part of a reform of ITU to give the Union greater flexibility to adapt to an increasingly complex, interactive and competitive telecommunications environment. ITU's three main areas of activity were organized in "Sectors": radiocommunications, telecommunication standardization and telecommunication development. Today, the work of the former CCIR continues to be carried out by the ITU-R Study Groups. Study Group 7 is termed "Science Services" which refers to the standard frequency and time signal, space research (SRS), space operation, Earth exploration-satellite (EESS), meteorological-satellite (MetSat), meteorological aids (MetAids) and radio astronomy (RAS) services. Study Group 7 develops ITU-R Recommendations, Reports and Handbooks that are used for development and ensuring non-interference operation of space operation, space research, Earth-exploration and meteorological systems (including the related use of links in the inter-satellite service), radio astronomy and radar astronomy, dissemination, reception and coordination of standard-frequency and time-signal services (including the application of satellite techniques) on a worldwide basis.

The ITU Telecommunication Standardization Sector (ITU-T) is a permanent organization of the ITU. ITU-T is responsible for studying technical, operating and tariff questions and issuing Recommendations on them with a view to standardizing telecommunications on a worldwide basis. The Study Groups of ITU-T assemble experts from around the world to develop international standards known as ITU-T Recommendations which act as defining elements in the global infrastructure of information and communication technologies (ICTs). The international standards (ITU-T Recommendations) developed by Study Group 15 detail technical specifications giving shape to global communication infrastructure. In the context of this Report, the ITU-T Recommendation series G-80x and the more recent G-827x series are particularly relevant.

The process to synchronize UTC with UT1 is described in Recommendation TF.460, the first version of which was adopted by the CCIR in 1970.

It should be noted that UTC is widely used in different radiocommunication systems and with this the ITU is concerned about its use since the consequences of any changes have global effect for telecommunication. It should be pointed out that several radiocommunication systems are used for safety and rescue of human lives.

In 2000, Question ITU-R 236-2/7 – The future of the UTC time scale, was adopted to carry out studies concerning the future of the UTC time scale. The relevant studies were conducted by ITU-R during the 2003-2007, 2007-2012 and 2012-2015 study cycles. Proposals were made to revise Recommendation ITU-R TF.460-6 by stopping the leap-second procedure in order to achieve a continuous uniform time scale.

A draft revision of Recommendation ITU-R TF.460-6 was reviewed by the Radiocommunication Assembly 2012 (RA-12) and, based on different views of administrations, it was decided to return the draft revision of the Recommendation to the ITU-R for further study of other technical options. It was recommended that additional studies should take account of broader implications and include consultations with other concerned organizations. Further, RA-12 decided to raise this matter to the World Radiocommunication Conference 2012 (WRC-12) to consider an agenda item on this topic for WRC-15. As a result, WRC-15 adopted agenda item 1.14 and the ITU-R was invited to carry out the relevant studies in accordance with Resolution **653 (WRC-12)**.

Based on the results of further studies, WRC-15 agreed to Resolution **655 (WRC-15)** that resolves to study the issue more widely in cooperation with the relevant international organizations. It also instructs the Director of the Radiocommunications Bureau (BR) to report on the progress of the studies to the World Radiocommunication Conference 2023 (WRC-23). The Resolution also resolves that until WRC-23, UTC as described in Recommendation ITU-R TF.460-6 shall continue to apply. Reference to Resolution **655 (WRC-15)** is made from Radio Regulations (RR) No. **1.14**.

Thus, currently in accordance with Resolution **655 (WRC-15)**, the ITU actively cooperates with the BIPM, the CIPM, the CGPM and also other relevant organizations to study more widely various aspects of current and potential future reference time scales including their impacts and applications. The results of these studies will be reported by the Director of the BR at the WRC-23.

2.2.2 BIPM, CIPM and CGPM

The Metre Convention (*Convention du mètre*) is a treaty that created the BIPM, an inter-governmental organization under the authority of the CGPM and the supervision of the CIPM. It was signed in Paris in 1875, modified slightly in 1921, and remains the basis of international agreement on units of measurement.

The CGPM meets every four to six years and is composed of delegates from all member states. It is the primary international meeting to represent interests of member states in the establishment of a standardized metric system as the basis of international commerce and exchange. The CGPM adopts resolutions relevant to the definition and realization of the SI. The CIPM is an advisory committee to the CGPM. It is made up of eighteen individuals, each of a different nationality. Over the years, the CIPM has set up a number of Consultative Committees, which bring together the world's experts in their specified fields as advisers on scientific and technical matters. The presidents of the Consultative Committees are appointed by, and are normally members of, the CIPM. Among the tasks of these Consultative Committees are the detailed consideration of advances in physics that directly influence metrology, the preparation of recommendations for discussion at the CIPM, the identification, planning and execution of key comparisons of national measurement standards, and the provision of advice to the CIPM on the scientific work in the laboratories of the BIPM. The Consultative Committee for the Definition of the Second (CCDS) was set up in 1956. Its name was changed to Consultative Committee for Time and Frequency (CCTF) by the CIPM in 1997. Present activities concern matters related to the definition and realization of the second, establishment and maintenance of International Atomic Time (TAI) and Coordinated Universal Time (UTC), and advice to the CIPM on matters related to time and time scales. The BIPM coordinates international metrology and the development of the metric system to ensure uniformity of standard measures around the world. The coordination by the BIPM is done through members representing the National Metrology Institutes (NMIs) of the Metre Convention's Member States, other relevant organizations and through its own laboratory work. The BIPM maintains the International System of Units (SI) and became responsible for generating and maintaining UTC in 1985. Previously UTC was established and maintained by the Bureau international de l'heure (BIH). National delegates at the 26th meeting of the CGPM (2018) unanimously adopted Resolution 2 – *On the definition of time scales*; therefore, Resolution 2 (CGPM 2018) contains the official definition of UTC.

UTC is generated by the BIPM from data provided by NMIs and other timing centres. For an international reference such as UTC, the requirement is extreme reliability, long-term frequency stability and accuracy. UTC therefore is realized from the largest possible number of atomic clocks of different types located in more than 80 institutes worldwide and connected by networks that allow precise time comparisons between these remote sites. By the inclusion of highly accurate primary frequency standards and other frequency sources from a dozen metrology institutes around the world, UTC is based upon the best realizations of the SI second. It is realized in real-time by local approximations maintained in timing centres designated as UTC(k) with k being the time centre's designation. The offsets between UTC and its local realizations UTC(k) are calculated after the fact at the BIPM. These UTC(k) realizations are used in disseminating time signals to users of precise time and those that need to know the current time or real time values.

2.2.3 IERS

Background

The International Earth Rotation and Reference Systems Service (IERS) was established in 1987 by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics

(IUGG). The primary objectives of the IERS are to serve the astronomical, geodetic and geophysical communities by providing the following:

– The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF);
– The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF);
– Earth orientation parameters (EOPs) required to study Earth orientation variations and to transform between the ICRF and the ITRF;
– Geophysical data to interpret time/space variations in the ICRF, ITRF or Earth orientation parameters, and model such variations;
– Standards, constants and models (i.e. conventions) encouraging international adherence.

Earth orientation parameters

Earth orientation parameters (EOPs) are the numbers that define the relationship between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). EOPs are comprised of three general motions with a total of five parameters: two polar motion components (PM-x, PM-y), the variable Earth rotation component (UT1), and corrections to the two celestial pole coordinates (dX, dY).

EOPs display a high level of variability due to a number of causes. Over periods of less than a couple of years, weather, oceans, and hydrology play a dominant role in the variations of Earth orientation. The mechanisms responsible for these variations are both a time-dependent distribution of mass (both water and air) as well as the change of angular momentum (again due to both water and air) to the solid Earth. Longer-term variations are generally caused by geophysical phenomena as well as by the gravity of the Moon and the Sun. As can be intuited, the effects of the forces causing changes to EOPs are highly variable and highly unpredictable. Even using the best atmospheric, oceanic and other Earth angular momentum observations and models, positive skill in predictions is only obtained out to a few weeks. Beyond that, some combination of deterministic and stochastic predictions are necessary to provide long-range EOP estimates.

EOPs have several practical purposes and are therefore used by many operational systems. EOPs are necessary inputs for modern day navigation systems such as global navigation satellite systems. They are also necessary for pointing ground-based detectors or antennas toward the correct part of the sky and they are necessary for pointing communication satellites toward the correct spot on the Earth. Because of these practical and real-time needs, many operational EOP users are more interested in EOP predictions than they are in after-the-fact EOP determinations.

Earth rotation determination

The variable Earth's rotation, UT1, can be determined by making careful ground-based observations of celestial objects. Very long baseline interferometry (VLBI) is used extensively because VLBI is the only technique that is capable of determining UT1 directly. Other techniques such as GNSS, satellite laser ranging (SLR), lunar laser ranging (LLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) can only determine parameters related to UT1 but cannot determine UT1 directly. By combining the measurements from techniques such as the VLBI, GNSS, SLR, LLR, and DORIS, it is possible to create a more accurate and more robust determination of all Earth orientation parameters, including UT1.

The IERS has two Centers that are responsible for providing EOPs to users. The Earth Orientation Centre (EOC), located at the *Observatoire* de Paris, is responsible for monitoring the long-term Earth orientation parameters, publication for time dissemination and the leap second announcements. The Rapid Service/Prediction Centre, located at the U.S. Naval Observatory, is responsible for providing orientation parameters on a rapid turnaround basis, primarily for real-time users and others needing the highest-quality EOP information sooner than that available in the final series published by the IERS EOC.

IERS Earth orientation parameter products

The IERS has created different EOP products in order to meet the needs of a variety of users, in the form of Bulletins and files with continuous series. Below is a brief summary of the IERS Bulletins:

– IERS Bulletin A – Contains rapid determinations for Earth orientation parameters;

– IERS Bulletin B – Contains monthly Earth orientation parameters;

– IERS Bulletin C – Contains announcements of the leap seconds in Coordinated Universal Time (UTC);

– IERS Bulletin D – Contains announcements of the value of DUT1 (= UT1 - UTC with 0.1 s resolution).

Continuous series include several "finals" series by the Rapid Service/Prediction Centre and the C04 series by the Earth Orientation Centre.

The dissemination methods for IERS products include hypertext transfer protocol (http) and file transfer protocol (ftp). See https://www.iers.org/EOP for a list of IERS EOP products.

Relation between UT1 and UTC

Historically, UTC has been constrained to be sufficiently close to UT1. To ensure this, leap seconds were inserted into UTC so that the difference |UT1 – UTC| < 0.9 s. The insertion of a leap second maintains the value of UT1 – UTC below the 0.9 s tolerance. A positive or negative leap second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September. Since 1972 there have been 27 leap seconds. More detailed information is given in Chapter 3.

The IERS, as the organization responsible for providing EOPs is tasked with determining the occurrence of leap seconds. The IERS must provide notification of impending leap seconds at least two months in advance although typically six-months' notice has been provided. Due to the variability of the Earth's rotation, it is difficult to predict the occurrence of the next leap second more than six months in advance.

More details provided by the IERS are given in Annex 2.

2.3 Other organizations associated with time scales and related standards

International organizations that have also been associated with time scales are the International Astronomical Union (IAU), the International Union of Geodesy and Geophysics (IUGG), the International GNSS Service (IGS) and the International Union of Radio Science (URSI), International Civil Aviation Organization (ICAO), International Maritime Organization (IMO), World Meteorological Organization (WMO), International Committee on GNSS (IGS), International Organization for Standardization (ISO). Some of them had established specific working groups to consider the future requirements and applications of the UTC time scale.

2.3.1 IAU

The IAU is a non-governmental international science organization primarily of researchers in the field of astronomy and astrophysics. Since time keeping was based traditionally on the rotation of the Earth with respect to stars, astronomers have had a long association with the determination of time. In fact, primary subjects of fundamental astronomy have been the construction of reference frames and time scales. The IAU has three commissions associated with time keeping in Division A – Fundamental Astronomy. They are Commission A1 on Astrometry, Commission A2 on Rotation of the Earth and Commission A3 on Fundamental Standards. A Division A Working Group (WG) on Time Metrology Standards was also established. The Commission 31 on Time previously established in 1922 was discontinued in 2015.

Astronomers are concerned about the relation between UT1 and UTC as UT1 is a representation of the Earth's Rotation Angle (ERA) describing the main part of the Earth rotation transformation from the International Terrestrial Reference Frame (ITRF) to the International Celestial Reference Frame (ICRF). To track celestial objects and predict their motions precise knowledge of ERA is required. The approximation of UT1 provided by UTC with a maximum error of 0.9 s has been used in low-accuracy applications.

2.3.2 IUGG

The IUGG is a non-governmental, scientific organization, established in 1919 as one of the 32 scientific unions presently grouped within the International Science Council (ICS, formerly ICSU). The IUGG is dedicated to the international promotion and coordination of scientific studies of the Earth and its environment in space. These studies include the shape of the Earth, its gravitational and magnetic fields, the dynamics of the Earth as a whole and of its component parts, the Earth's internal structure, composition and tectonics, earthquakes and elastic wave propagation, the generation of magmas, volcanism and rock formation, the hydrological cycle including snow and ice, all aspects of the oceans, the atmosphere, ionosphere, magnetosphere and solar-terrestrial relations, and analogous problems associated with the Moon and planets.

The IUGG is comprised of eight semi-autonomous associations, each responsible for a specific range of topics or themes within the overall scope of Union activities. In addition, the IUGG establishes inter-association commissions and relationships with several other scientific bodies with similar interests. The IUGG involvement in issues related to international time scales, and more specifically UTC, are basically, (a) as users of these time scales both for the time tagging of measurements and the use of "time" as an argument in models, and (b) in a supporting role of space geodesy in the realization of UT1. The association dealing with geodesy (International Association of Geodesy, IAG) is specifically concerned by this subject. In addition, the IUGG has a formal liaison to the BIPM through the CCTF; this committee that advises the CIPM on matters related to time and time scales, is one of the international organizations with which the IUGG has a formal liaison.

2.3.3 IGS

The International GNSS Service (IGS) is a scientific conglomerate of various government and academic institutions around the world. Its primary mission is the computation and publication of precise GNSS orbits, clock and geophysical parameter estimates for use in high precision applications. The standards for both the terrestrial reference frame and time are both very important to ensuring that the published products are interpreted correctly and to the best accuracy possible against internationally recognized standards.

The IGS is committed to providing the highest quality orbit and clock products that it can possibly achieve on the publication schedule for each product. The core products consist of final, rapid and ultra-rapid products which are released on a weekly, daily and sub-daily basis, respectively (see www.igs.org for details). The generation of these core products utilizes GNSS observations collected at approximately 500 IGS sites around the globe. Data Centres receive and store these observations and then IGS Analysis Centres (AC) retrieve, and compute orbit and clock offset solutions of GNSS vehicles as well as position and clock offset solutions of ground stations at the antenna phase centre.

A comprehensive description of the IGS is provided in Teunissen & Montenbruck (2017).

2.3.4 URSI

Radio science encompasses the knowledge and study of all aspects of electromagnetic fields and waves. The International Union of Radio Science (*Union Radio-Scientifique Internationale*), a non-governmental and non-profit organization under the International Council for Science, is responsible for stimulating and coordinating, on an international basis, studies, research, applications, scientific exchange, and communication in the fields of radio science.

The achievement of the objectives of the Union within particular parts of the fields of radio science is the responsibility of the Scientific Commissions established by the Council. Scientific Committees of the Union are established by the Council to deal with matters which are of interest to several Commissions.

URSI Commission A – Electromagnetic metrology promotes research and development of the field of measurement standards and physical constants, calibration and measurement methodologies, improved quantification of accuracy, traceability, and uncertainty. Areas of interest include:

– the development and refinement of new measurement techniques and calibration standards;

– primary standards, including those based on quantum phenomena, and the realization and dissemination of reference time and frequency standards;

– measurements in advanced communication systems, space metrology and other applications, including antenna and propagation measurement techniques.

URSI Commission A fosters the best practices and training for accurate and consistent measurements needed to support research, development, and exploitation of electromagnetic technologies across the spectrum and for all commissions.

The activities of URSI include the study of topics relevant to the advancement of telecommunications, some of which are of direct interest to the ITU.

2.3.5 International Civil Aviation Organization (ICAO)

The International Civil Aviation Organization (ICAO) is a UN specialized agency, established in 1944 to manage the administration and governance of the Convention on International Civil Aviation (Chicago Convention). It works with the Convention's to reach consensus on international civil aviation Standards and Recommended Practices (SARPs) and policies in support of a safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector. These SARPs and policies are used by ICAO Member States to ensure that their local civil aviation operations and regulations conform to global norms. ICAO also coordinates assistance and capacity building for States in support of numerous aviation development objectives; produces global plans to coordinate multilateral strategic progress for safety and air navigation; monitors and reports on numerous air transport sector performance metrics; and audits States' civil aviation oversight capabilities in the areas of safety and security. The establishment and maintenance of international SARPs, as well as Procedures for Air Navigation (PANS), are fundamental tenets of the Convention on International Civil Aviation and a core aspect of ICAO's mission and role.

2.3.6 International Maritime Organization (IMO)

The main mission and responsibility of the International Maritime Organization (IMO) are to develop and preserve a comprehensive framework of regulations and policies for the shipping industry and its activities like maritime security, safety, technical cooperation, environmental concerns and legal matters. The governing body of the IMO is an assembly that meets bi-yearly. The assembly comprises all the member states. In the intervening time between the Assembly sessions, a council acts as the governing body. This council comprises of 40 member states who are elected by the assembly for a specified period of time. With regard to UTC the IMO appears to be concerned with the accuracy of electronic navigational systems with respect to navigational charts.

Time in navigation is necessary for getting the position on the sea surface, as well as to determine the water level under the keel depending on the tides.

As of 2014 [IMO 2014], over 90% of world trade is transported by sea. This totals some 7 500 million tonnes (32 000 000 million tonne-miles), of which about 33% is oil, 27% is bulk (ore, coal, grain and phosphates), the remaining 40% being general cargo. Operating these merchant ships generates an estimated annual income of $380 000 million in freight rates within the global economy, amounting to 5% of total world trade. The industry employs over 1.2 million seafarers.

2.3.7 World Meteorological Organization (WMO)

The World Meteorological Organization (WMO) is an intergovernmental organization that originated from the International Meteorological Organization (IMO), the roots of which were planted at the 1873 Vienna International Meteorological Congress. Established by the ratification of the WMO Convention on 23 March 1950, WMO became the specialised agency of the United Nations for meteorology (weather and climate), operational hydrology and related geophysical sciences a year later.

2.3.8 International Committee on GNSS (IGS)

The International Committee on Global Navigation Satellite Systems (ICG), established in 2005 under the umbrella of the United Nations, promotes voluntary cooperation on matters of mutual interest related to civil satellite-based positioning, navigation, timing, and value-added services. The ICG contributes to the sustainable development of the world. Among the core missions of the ICG are to encourage coordination among providers of GNSS, regional systems, and augmentations in order to ensure greater compatibility, interoperability, and transparency, and to promote the introduction and utilization of these services and their future enhancements, including in developing countries, through assistance, if necessary, with the integration into their infrastructures. The ICG also serves to assist GNSS users with their development plans and applications, by encouraging coordination and serving as a focal point for information exchange.

2.3.9 International Organization for Standardization (ISO)

International Organization for Standardization (ISO) is an independent, non-government organization the members of which are the standards organizations of the 164 member countries. It is the world’s largest developer of voluntary international standards, and it facilitates world trade by providing common standards among nations. It began in the 1920s as the International Federation of the National Standardizing Associations (ISA). It was suspended in 1942 during World War II, but after the war ISA was approached by the recently-formed United Nations Standards Coordinating Committee (UNSCC) with a proposal to form a new global standards body. In October 1946, ISA and UNSCC delegates from 25 countries met in London and agreed to join forces to create the new International Organization for Standardization. The new organization officially began operations in February 1947. International Standard 8601-1:2019 specifies numeric representations of date and time. This standard notation helps to avoid confusion in international communication caused by different national notations and increases the portability of computer user interfaces. The Technical Committee in charge of ISO 8601 is ISO TC 154, Processes, data elements and documents in commerce, industry and administration.

3 Description of current and potential future reference time scales

3.1 Description of current time scales including reference time scale

The rotation of the Earth with respect to the Sun has been the basis for the realization of conventional time scales since antiquity. Mechanical clocks and modern atomic frequency standards have been related to the Earth's rotation by evolving conventional practices. This section is intended to provide technical background information on the development of time scales away from the conventional astronomically derived ones toward those maintained by atomic clocks. Those based on celestial motions had been given the role of "reference time scale" in the past, as Universal Time and Ephemeris Time; they are still in use for many applications. The advent of atomic time introduced the current reference time scale UTC and involved the need to relate the various time scales in the frame of general relativity.

3.1.1 Solar time

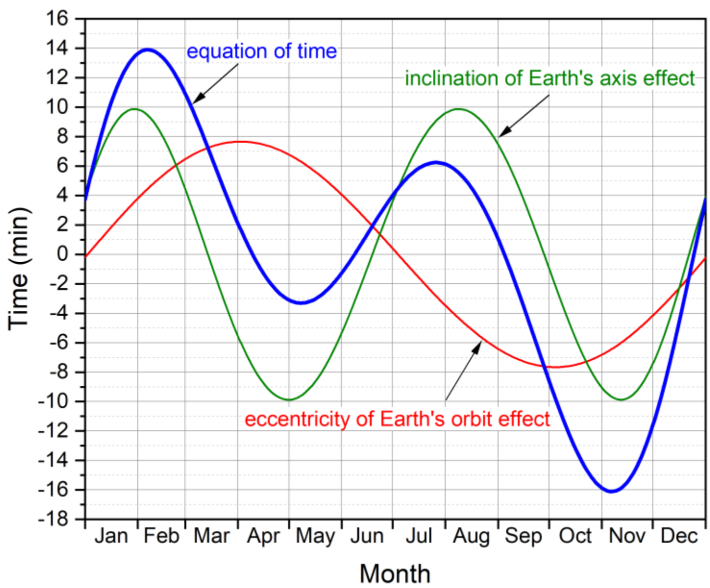
Apparent solar time measured by astronomical observations of the meridional passage of the Sun at the location of the observer results in a wide range of location-dependent time scales. It was already realized in ancient times that using observations of the actual Sun to measure time resulted in measurements of the length of a day that varied during the year. We now know this is caused by the inclination of the Earth's axis to the plane of its orbit and by the eccentricity of the Earth's elliptical orbit. To achieve a more standardized time, mean solar time, based on an adopted mathematical expression for the concept of a fictitious mean Sun that would complete one revolution along the celestial equator in the same time interval as the actual Sun completes its annual motion along the ecliptic, was devised.

The difference between mean solar time and apparent solar time, called the equation of time is shown in Fig. 1. The maximum amount by which apparent noon precedes mean noon is about 16.5 minutes around 3 November and the maximum amount by which mean noon precedes apparent noon is about 14.5 min around 12 February (Nelson, *et al.*, 2001).

Both apparent and mean solar time are defined by astronomical observations with respect to the local meridian. Stimulated by the growing network of railroads and the need to coordinate the schedules among them, a standardized time was adopted based on the establishment of a prime meridian (Greenwich) and time zones around the Earth (Blaise, 2000).

FIGURE 1

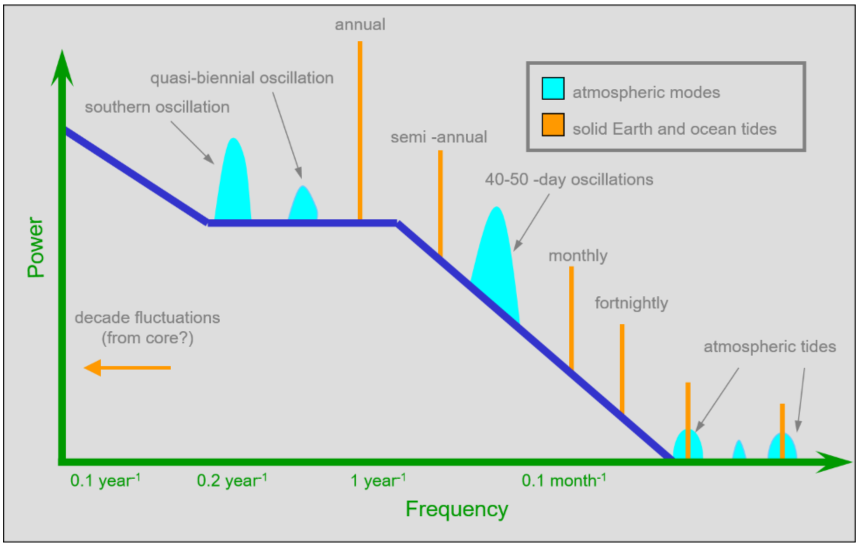
The equation of time
***Annuaire du Bureau des longitudes*, Guide des données astronomiques 2020, IMCCE/BDL et EFP Sciences, 2019, 42-43**



Astronomical observations have shown that mean solar time is not uniform because of variations in the Earth's rotational speed. A wide spectrum of quasi-random and periodic fluctuations in the Earth's rotation has been documented [McCarthy *et al.*, 2018] and is illustrated in Fig. 2. These include the secular variation due to a combination of tidal friction and glacial isostatic adjustment slowing the Earth's rotational speed and lengthening of the day by about 0.000 5 s to 0.003 5 s per century, irregular changes apparently correlated with physical processes occurring within the Earth, and higher-frequency variations known to be largely related to the changes in the total angular momentum of the atmosphere and oceans. Periodic variations associated with tides are also present.

FIGURE 2

Spectrum of Earth's rotational frequency harmonics and the forces attributed to them



From astronomical observations beginning in the 1600s it was clear that the Earth's rotation rate was slowing, and it was attributed finally in the 1800s to the tidal retardation of the Earth's rotation and the consequent variation in the orbital velocity of the Moon due to the conservation of angular momentum. Stephenson and Morrison (1995) show that over the past 2 700 years, the Length of the Day (LOD, *the excess of a UT1 day from 86 400 seconds*) has increased at an average rate of 1.7 ms per day per century and that geophysical analysis of tidal braking indicates that lunar tidal deceleration should contribute an increase of 2.3 ms per day per century. The difference of 0.6 ms per day per century is apparently caused by the changing shape of the Earth resulting from glacial melting. (See Fig. 3.)

The periodic variation in the Earth's rotation rate is better visible in a zoom into more recent years, shown in Fig. 4, and is associated with the circulation of the atmosphere, which causes a seasonal variation in LOD on the order of 0.5 ms peak-to-peak about the mean. The rotation of the Earth runs slow by about 30 ms in May and runs fast by a similar amount in November. The LOD of the Earth drops by about 1 ms from May to August and increases by a similar amount from September to January. The Earth's LOD is also subject to frequent apparently random changes of less than a few tenths of a millisecond per day that can persist for about a decade. A comprehensive discussion is given by Stephenson (1997).

FIGURE 3

Excess LOD since the 1600s

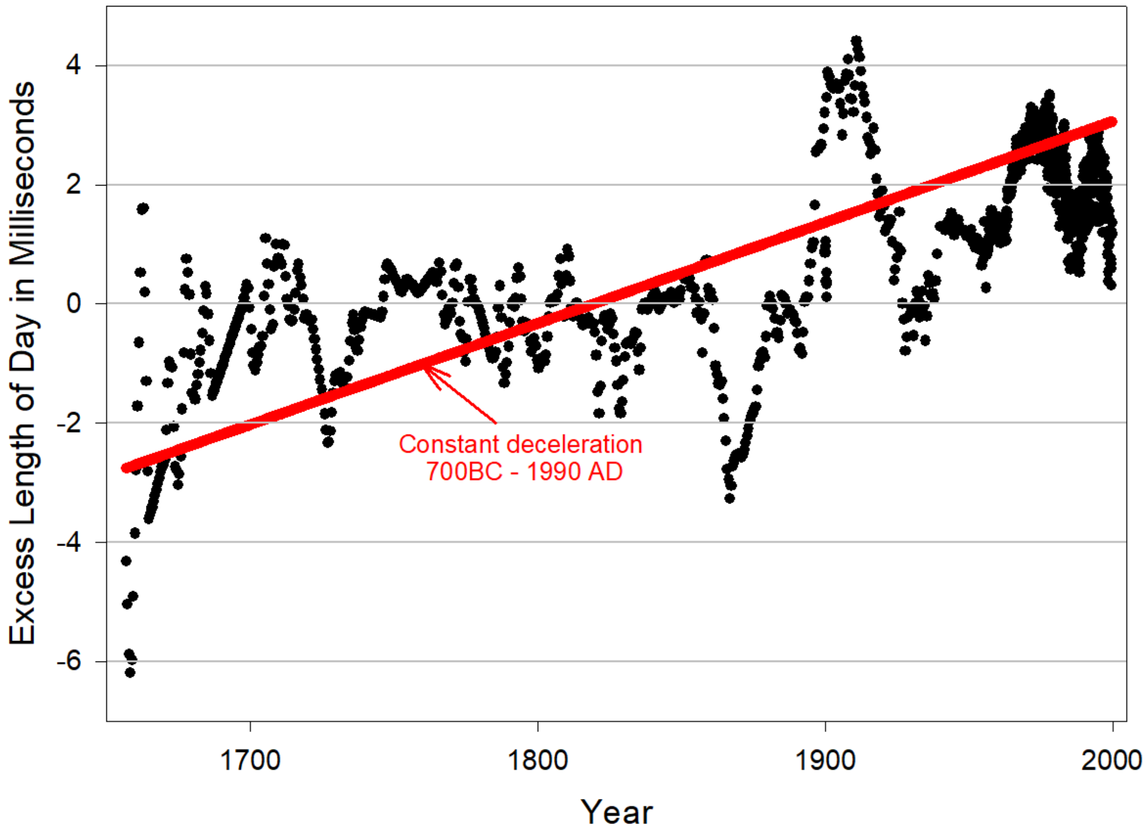
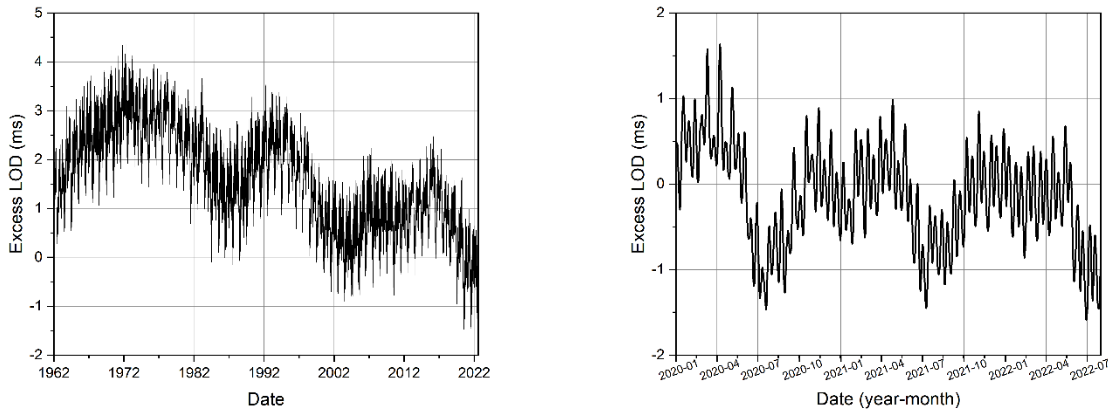


FIGURE 4

Excess LOD since 1962 (left), including secular linear change and during 2020, 2021 and until end of July 2022 (right)
Source of data: IERS, EOP_14_C04



The Earth's rotation is measured by a quantity called "Earth Rotation Angle," the angle of the prime meridian of the International Terrestrial Reference Frame (ITRF) – or of its intersection with the intermediate equator, the Terrestrial Intermediate Origin (TIO) – with respect to the Celestial Intermediate Origin (CIO) located in the same plane. It is linearly related to UT1, which is referred to as a time scale. By definition:

$$ERA = \Omega_1 \, UT1 + ERA_0$$

where Ω_1 is the nominal Earth angular velocity, conventionally corresponding to the mean solar day of the 1820 epoch, given by $\Omega_1 = 2\pi \cdot 1.002\ 737\ 811\ 911\ 354\ 48$ rad/*d* (*d* corresponds to 86 400 s of the SI). Practically, UT1 is not measured, but its difference with respect to TAI or any other atomic time scale is determined.

The results are always disseminated under the form of UT1 – UTC.

3.1.2 Ephemeris time

To attempt to realize a more uniform time scale a new time scale was devised in the 1950s known as Ephemeris Time (ET). It was originally conceived as a nonrelativistic astronomical time scale realized by the motions of the celestial bodies in the solar system (Clemence, 1971). This time scale promised a more stable and uniform time scale but the development of atomic standards around the same time soon overtook the search for a more uniform astronomical time scale. Atomic clocks operating in the timing centres offered a more stable and a more easily realizable method of generating and maintaining time.

ET may be characterized as the measure of time that brings the observed positions of celestial bodies into alignment with their positions listed in an astronomical ephemeris that are computed according to the Newtonian laws of dynamics. It was then defined by those laws of motion (*Explanatory Supplement 1961*, p. 68). On the basis of Newcomb's formula for the geometric mean longitude of the Sun, the second of ET was defined by the 11th CGPM in 1960 as "the fraction 1⁄31 556 925.974 7 of the tropical year for 1900 January 0 at 12 h ephemeris time" (BIPM, 2006, p. 149). Newcomb's formula was derived from astronomical observations performed over the interval from 1750 to 1892 (Newcomb, 1895). Consequently, the second of ET had the same duration as a second of UT1 that would have been observed in about 1820, the approximate mean epoch of the observations analysed by Newcomb. Incidentally it should be noted that 1900 was the epoch of a tropical year of 31 556 925.974 7 s of ET, while 1820 was the epoch of a LOD of 86 400 s of UT1.

3.1.3 Atomic time

Following the appearance of the first operational Caesium beam frequency standard in 1955 at the National Physical Laboratory (NPL) in the U. K. (Essen and Parry, 1957), the Royal Greenwich Observatory (RGO), U.S. Naval Observatory (USNO), and U. S. National Bureau of Standards (NBS) began to produce atomic time scales. The details of the development of these scales are contained in Nelson, *et al.* (2001).

Atomic time has become the basis of all modern time scales and has been maintained continuously in various laboratories since 1955 although not formally adopted until 1971 as an international time scale.

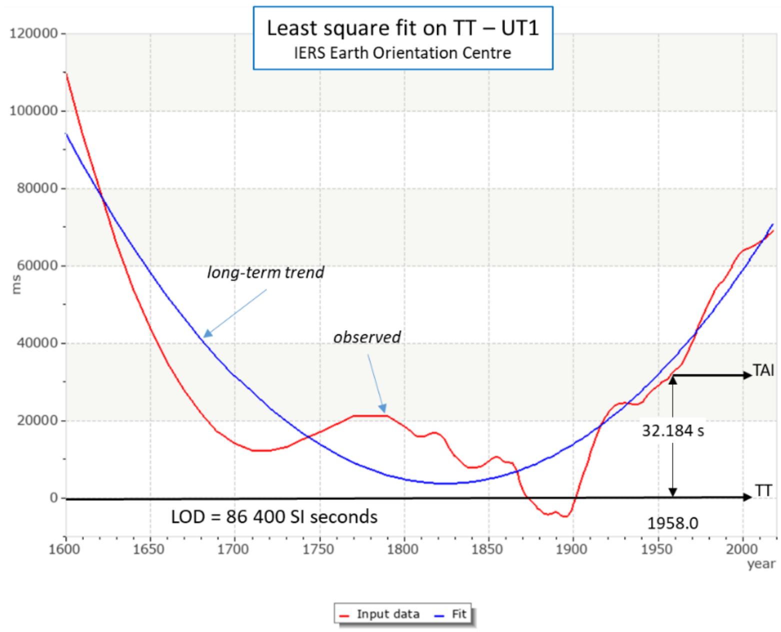
3.1.4 International Atomic Time

International Atomic Time (*Temps atomique international*, TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000) (*Trans. Int. Astron. Union*, Vol. XXIV B, 2001) and a time offset of 32.184 s due to historical reasons. The formation of TAI was recommended by the IAU in 1967, the URSI in 1969 and the International Radio Consultative Committee (CCIR) of the ITU in 1970. The 14th CGPM (CGPM 1972) approved the establishment of TAI in 1971 as the coordinate time scale whose unit interval is the second of the SI as realized on the rotating geoid. Resolution 2 (CGPM 2018) gives the official definitions of TAI and UTC.

The fact that TAI is a coordinate time scale was stated by the CCDS in 1970 (BIPM 1971). The necessary relativistic modelling is used in the establishment of TAI, e.g. in the processing of time transfer techniques and in the use of primary frequency standards that provide TAI accuracy. The accuracy of TAI is a primary consideration in maintaining the SI second and providing a reliable metrological scale in the long term. The optimization of the long-term stability is done at the expense of short-term accessibility. The comparison of UT1 to TT extrapolated back to 1600 is shown in Fig. 5, reproduced from the IERS Earth Orientation Centre.

FIGURE 5

Observations and parabolic fit of TT – UT1 versus time, since 1600 (IERS Earth Orientation Centre)



3.1.5 Coordinate time scales

The astronomical time scales discussed thus far were based primarily upon the dynamics of the Earth and other bodies in the solar system according to Newtonian dynamics. The concept of time scales for dynamical theories and for ephemerides was redefined in 1976 when the IAU recognized that the time scales for dynamical theories (referred to the centre of mass of the Solar System) and for apparent geocentric ephemerides had to be determined consistently with the general theory of relativity (*Trans. Int. Astron. Union*, Vol. XVI B, 1977). The time scale for apparent geocentric ephemerides was determined to be TAI + 32.184 s, while the time-like argument for dynamical theories in the Solar System was to be determined by a relativistic transformation so that there be only periodic variations with the geocentric time scale. At the next IAU General Assembly in 1979, these time scales were named Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB), respectively (*Trans. Int. Astron. Union*, Vol. XVII B, 1980). In 1984, TDT replaced ET as the tabular argument of the fundamental geocentric ephemerides. It has an origin at 1 January 1977 0 h TAI where its value is 1 January 0 h 00 min 32.184 s exactly, with a unit interval equal to the SI second, so that it maintains continuity with ET. As TDB was defined to differ from TDT by only periodic variations, a scaling factor is to be determined between them, which depends on the adjustment. Periodic variations have amplitudes less than 0.002 s and must be taken into account, generally in the form of series of Fourier components.

In 1991, the IAU renamed TDT simply Terrestrial Time (TT). A practical realization of TT in terms of TAI, is TT = TAI + 32.184 s (*Explanatory Supplement to the Astronomical Almanac*, rev. ed., 1992). The constant offset represents the difference between ET and UT1 at the defining epoch of TAI on 1 January 1958. In practice any difference between TAI + 32.184 s and TT is a consequence of the performance of the participating atomic time standards. In most cases, and particularly for the publication of ephemerides, this deviation is negligible. In 1991, the IAU General Assembly explicitly introduced the general theory of relativity as the theoretical basis for the celestial reference frame and the form of the space-time metric was specified (*Trans. Int. Astron. Union*, Vol. XXI B, 1992). At that time, it also clarified the definition of TT and defined two new time scales, Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB) (Seidelmann and Fukushima, 1992) as "coordinate" time scales (in the relativistic sense) to be used in the geocentric reference system and in the barycentric reference system, respectively. The time scales previously called "dynamical" TDT (now TT) and TDB should also be considered as coordinate time scales, but differing in rate from TCG and TCB, respectively. Geocentric time scales (TCG, TT) and barycentric ones (TCB, TDB) are related by four-dimensional space-time coordinate transformations (*IERS Conventions 2010*). These definitions were further clarified and expanded to provide higher accuracy by resolutions adopted at the IAU General Assembly in 2000 (*Trans. Int. Astron. Union*, 2001).

To within 10^{-18} in fractional frequency, TCG is related to TT by the expression:

$$TCG - TT = L_G \cdot (Julian\ Date - 2\,443\,144.5) \cdot 86\,400\ \mathrm{s}$$

where the defining value of L_G, chosen at the IAU GA in 2000 to provide continuity with the previous definition of *TT* so that its measurement unit agrees with the *SI* second on the geoid, is $6.969\,290\,134 \times 10^{-10}$ (*IERS Conventions 2010*).

3.1.6 Coordinated Universal Time

Direct comparison of time scales worldwide became available in about 1961 by means of long-range navigation systems and Earth orbiting satellites. The nautical almanacs of the UK and the USA were combined in 1957, beginning with the editions for 1960. In August 1959, it was also agreed to coordinate their time and frequency transmissions. Coordination began on 1 January 1960. Although the U.S. Naval Observatory (USNO) and the Royal Greenwich Observatory (RGO) began the original coordination effort, other institutions gradually began to participate, including the National Bureau of Standards (NBS), the Naval Research Laboratory (NRL) and National Physical Laboratory (NPL). Eventually, other countries joined the system, which was entrusted to the BIH in 1961. In January 1965, the BIH decided to attach UTC to its atomic time A3 (which later became TAI) by a mathematical relationship. This was the origin of the link between TAI and UTC. The name "Coordinated Universal Time (UTC)" was approved officially by a resolution of IAU Commissions 4 and 31 at the 13th General Assembly in 1967 (Nelson, *et al*., 2001). The BIH, began using measurements of clock comparisons made by means of long-range navigation systems and other systems to produce UTC. When TAI was established as a continuous time scale in 1958, decoupled from the rotation of the Earth, it was related to UTC. Coordination details were agreed through the CCIR of the ITU in 1962.

The current realization of UTC was recommended by the CCIR in 1970 and reported in ITU-R TF.460 as a compromise time scale between UT1 and TAI. Such a scale was to be used to coordinate broadcast time signals between timing centres and nations that could provide reasonably close agreement to UT1. This broadcast time scale is a compromise to provide both the SI second as its scale unit and an approximation to UT1 for celestial navigators to be accessible by radio transmissions. In 1972, it was in practice adopted and since then we have been used to one-second steps (Leap Seconds) in UTC to maintain agreement with UT1 within 0.9 s. Adjustment of UTC is made whenever the difference between UTC and UT1 approaches the value of 0.9 s. A positive or negative leap second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September. As UT1 is based on observations of the Earth's motion the adjustments in UTC occur at irregular intervals and require manual intervention in systems using UTC for operation and synchronization. The quantity DUT1 was defined to be the low precision predicted difference, DUT1 ~ UT1 – UTC, in integral multiples of 0.1 s to be broadcast or communicated in data messages. A user who needs UT1 could then adjust his time by receiving UTC-based signals to an accuracy of < 0.1 s. The procedures were adapted for time and frequency broadcast services for radio-telecommunication purposes at the time of adoption.

Today, the process to synchronize UTC with UT1 is described in Recommendation ITU-R TF.460-6, which is incorporated by reference in the Radio Regulations through Resolution **655** (**WRC-15**). According to this Recommendation, "The UTC is adjusted by insertion or deletion of seconds (positive or negative leap seconds) to ensure approximate agreement with UT1". It confirms that today UTC is a stepped atomic time scale produced by the BIPM that agrees in rate with TAI but differs by an integral number of seconds. UTC is defined in Resolution 2 (CGPM 2018). It is the international reference time scale for all practical timekeeping in the modern world. The relationship of the various time scales discussed is shown in Fig. 6. More of the history and development of these time scales is discussed in Nelson *et al.* (2001).

FIGURE 6

Progression of astronomical and atomic time scales

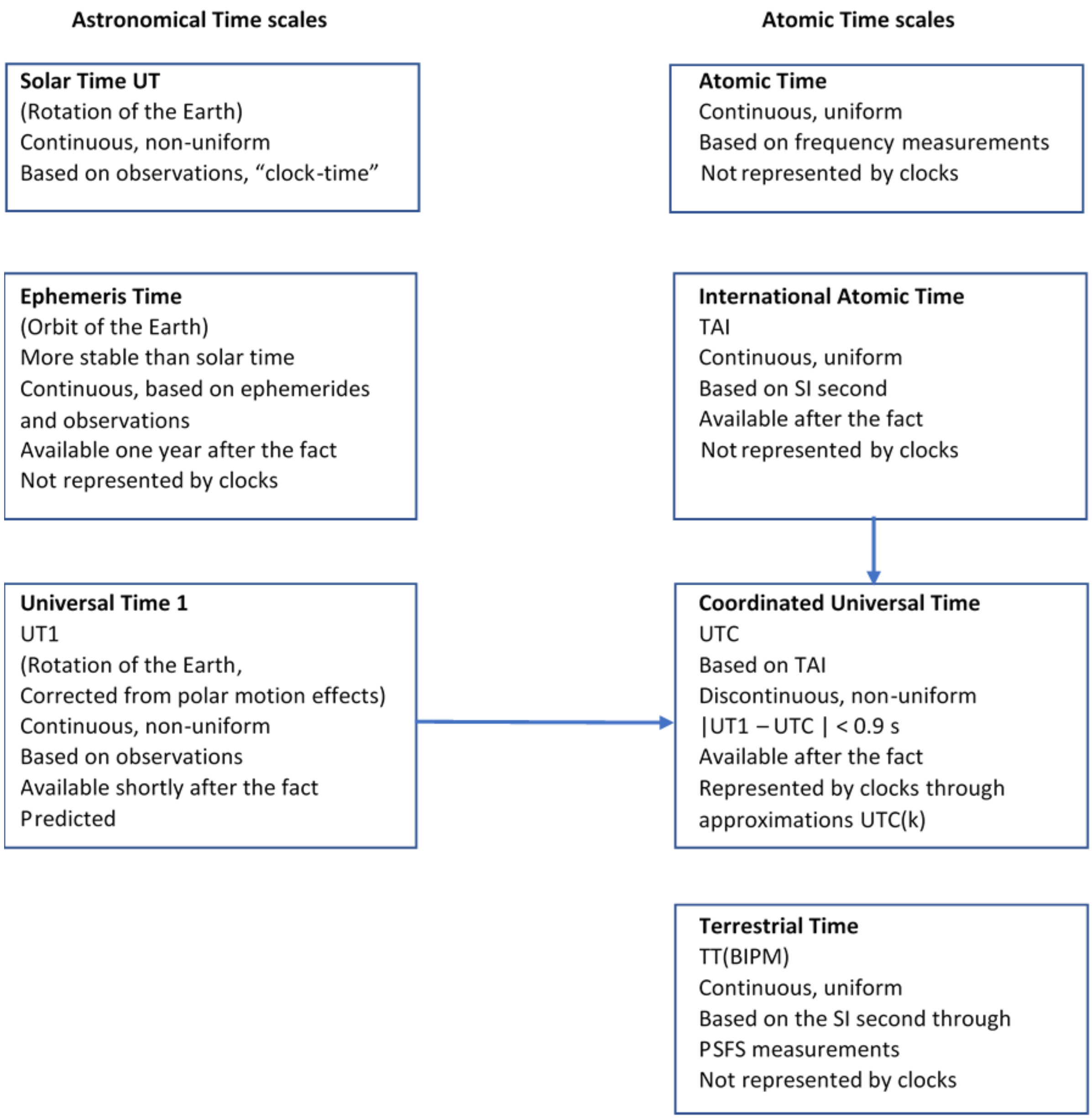


Figure 7 shows the difference between UT1 and UTC, starting from the initial implementation of UTC prior to 1972 without adjusting for leap seconds. During the early usage it was attempted to keep UT1 close to UTC by adjusting both the frequency offset and fractional second step adjustments to more closely match broadcast of atomic time signals with the Earth's rotation. This is evident in the first part of the curve shown in Fig. 7. Close coupling to the Earth's rotation was considered necessary to aid celestial navigation, however the system was difficult to coordinate between broadcast stations and the provision of a uniform accurate reference time.

The red curve in Fig. 8 represents the values of UT1 – UTC, in milliseconds, extracted from the IERS series of Earth Orientation Parameters EOP C04 (IERS/EOP/C04) between January 2016 and August 2022. The blue curve is the IERS prediction of values of UT1 – UTC until September 2023. The last positive leap second inserted on UTC on 1 January 2017 is visible. The effect of the increasing length of the day on UT1 – UTC is visible until mid-2019. Since then, we observe a rather stable behaviour, that made unnecessary the insertion of leap seconds; the prediction shows a change in the slope, suggesting that in the future the length of day could decrease, and even a negative leap second could be inserted.

Figure 9 shows the relation between TAI and UT1 and UTC, respectively.

FIGURE 7

UT1 – UTC in seconds, data from the EOP series C04, IERS

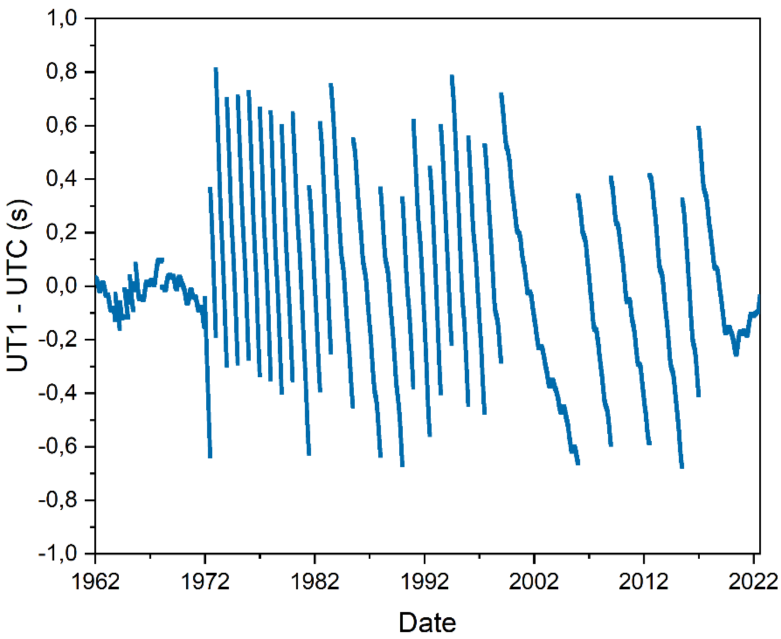


FIGURE 8

Daily values of UT1 – UTC in milliseconds computed (red curve) for the interval January 2016 – August 2022, and predicted (blue curve) for the interval September 2022 – September 2023, data from the IERS Rapid Service Centre

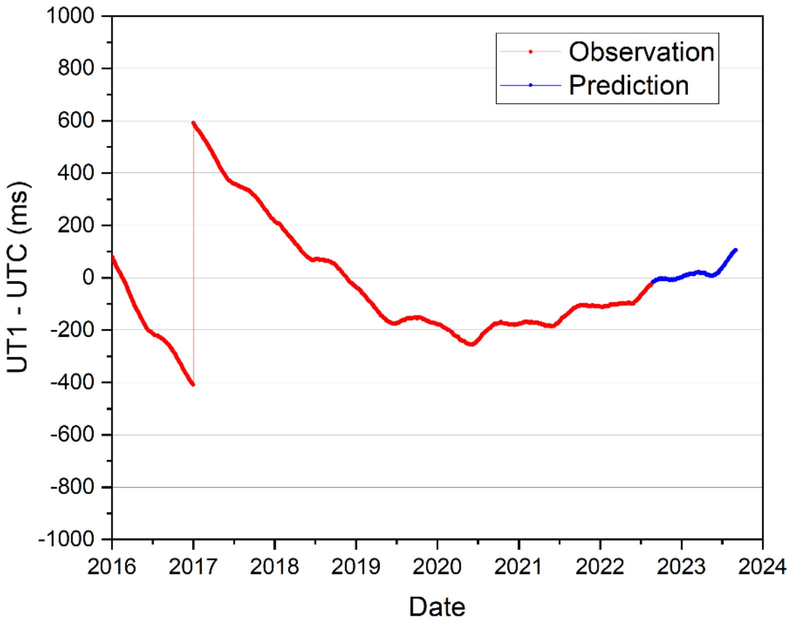
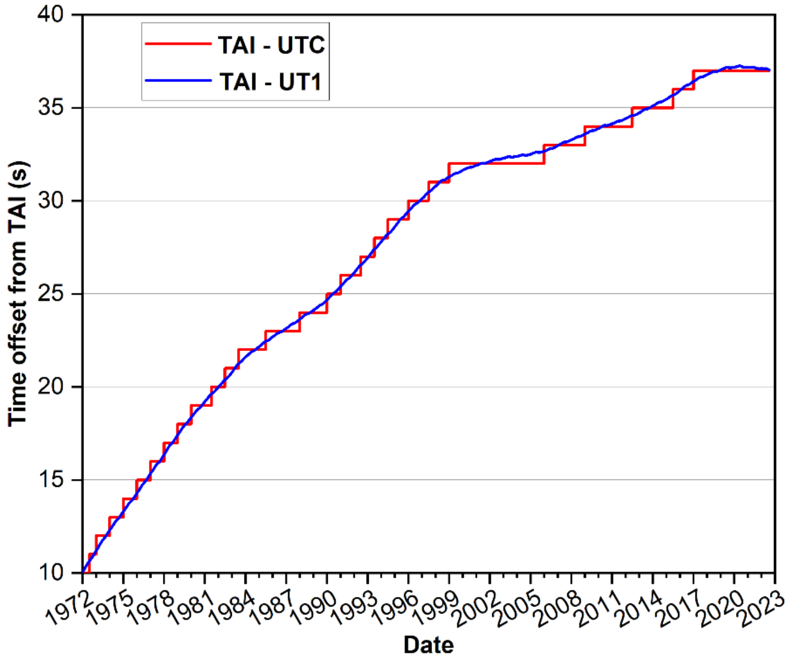


FIGURE 9

UT1 and UTC Time offset from TAI



What follows is a brief description of the current way of realization and dissemination of UTC, in some more detail as given in § 2.2.2. UTC is a time scale produced now by the BIPM with the same rate as TAI but differing from TAI only by an integral number of seconds. UTC is defined in Resolution 2 (CGPM 2018) and its production comprises several steps. Clock comparison data are now sent to the BIPM from more than 450 atomic clocks operated in some 80 standards laboratories involved in time metrology around the world every month. The data intervals are five days with measurements provided on days with the Modified Julian Date (MJD) ending in either 4 or 9. The process is illustrated in Fig. 10.

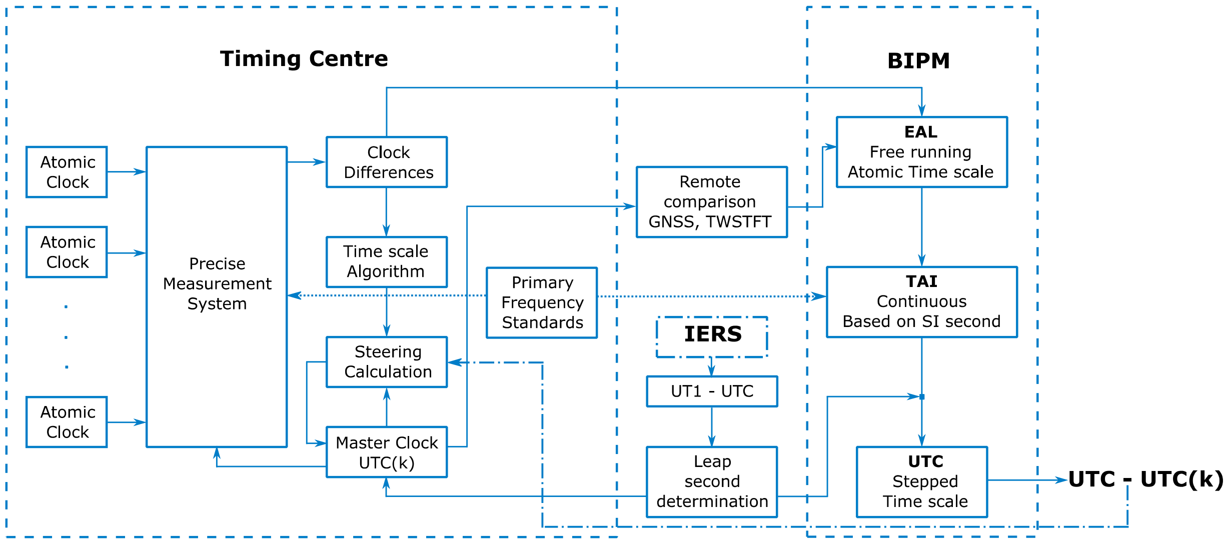
TAI is the basis of UTC. Its determination is performed in three steps:

1) Calculation using a post processing, iterative procedure of an intermediate scale, known as *Echelle Atomique Libre* (EAL) or Free Atomic Scale, using the clock comparison data from the participating time centres. Clock weights that are based on predictability are assigned in order to maintain the long-term stability of the time scale (Panfilo, 2014).
2) The frequency of EAL is evaluated using data from primary frequency standards that best realize the SI second.
3) TAI is then produced from EAL by applying, if necessary, a correction to the scale interval of EAL to give a value as close as possible to the SI second. Correcting of the scale unit is known as 'steering'.

As explained before, the IERS determines the need for adjusting the difference of UT1 and UTC to within an established tolerance of 0.9 s, thus introducing leap seconds in UTC.

FIGURE 10

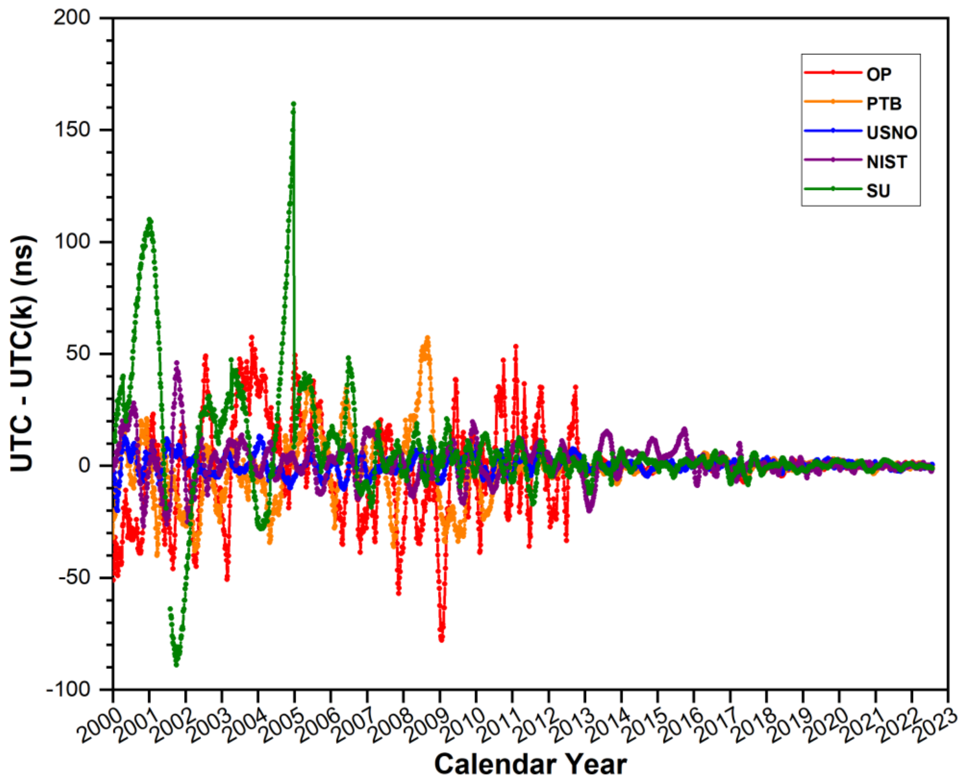
Diagram of the process of realizing UTC



UTC itself is not realized with any physical clock. Timing centres produce physical approximations of UTC with the nomenclature UTC(k). Each of the timing centres follows its specific recipe to get an accurate and predictable time scale (termed Master Clock in Fig. 10) from its available resources. For example, UTC(USNO) is the delivered real-time prediction of UTC as maintained by U.S. Naval Observatory. Representative values from a few selected timing centres of UTC - UTC(k) are shown in Fig. 11 (OP: *Observatoire de Paris*/LNE-SYRTE, Paris, France, PTB: Physikalisch-Technische Bundesanstalt, Braunschweig, Germany, USNO: US Naval Observatory Washington DC, USA, NIST: National Institute for Standards and Technology, Boulder (CO), USA, SU: VNIIFTRI, Mendeleevo, Russia). The plot is based on the results of differences UTC – UTC(k) which are published monthly in the BIPM Circular T (https://www.bipm.org/en/time-ftp/circular-t). UTC is thus physically realized by approximations in time laboratories and disseminated through standard frequency and time signal emissions as described in Recommendations ITU-R TF.768 – Standard frequencies and time signals, and ITU-R TF.583 – Time codes. See § 4 for details. As will be detailed in § 4.2.5, signals transmitted from GNSS satellites are today the most convenient and most frequently used source of access to UTC.

FIGURE 11

UTC(k) values for selected sites from BIPM Circular T



UTC obviously is the reference in standard frequency and time signal emissions. In addition, UTC has been recognized as the basis of civil time in resolutions and recommendations of intergovernmental organizations (ITU, CGPM) and scientific unions (IAU, URSI). UTC is also the basis of legal time according to many national legal codes throughout the world.

3.2 Motivation for changing the leap-second procedure

The practice of adjusting UTC by inserting leap seconds so as to limit the difference between UT1 and UTC to less than 0.9 s has resulted in increasing difficulties in several sectors. The discussion to change the current leap-second procedure is an attempt to address these difficulties while maintaining a link between UT1 and UTC. A detailed discussion of this question is in § 6.

3.3 Description of potential future reference time scales

International and national timekeeping is critical in every country for the correct synchronization of information and communication systems. The resilience of time synchronization has been recognized as crucial to many aspects of critical national infrastructure, such as telecommunications, energy distribution, and the timing of financial transactions.

To satisfy all these applications, the future reference time scale should be

– internationally realized,

– universally accepted, and

– continuous (at least for a long time).

It is also important that the future reference time scale has a known relation with the rotation of the Earth, and that its offset from UT1 is well known and disseminated.

Taking into account the importance to many aspects of critical national infrastructures, clear measures are needed to address the backward compatibility issue if a decision of future reference time scale is made.

A future reference time scale which satisfies the advantages of the legacy UTC and the requirements expressed above, could be obtained by maintaining the current UTC and by relaxing the limitation on the offset between UT1 and UTC. Thereby civil time will not be decoupled from Earth's rotation, but only the offset UT1 – UTC is extended.

The accurate knowledge of the EOP is ensured by the IERS including the continuous monitoring of UT1 and dissemination of UT1 – UTC. The IERS computes the value and disseminates it through the internet. The IERS plans further dissemination in collaboration with network time synchronization community and GNSS operating agencies.

The name "Coordinated Universal Time", and acronym "UTC" should be kept since the definition of the time scale remains the same as stated in the CGPM 2018 Resolution 2, the only change being the relaxation of its offset to UT1.

The maximum value of the extended offset UT1 – UTC should be defined by taking into account the constraints of the technological systems that will disseminate this value. Ideally this value should cover a long period of time (no less than 100 years). For example a two-digit integer number of seconds in UT1 – UTC may cover the next 500 years.

There is a view that the current DUT1 transmission scheme as in Recommendation ITU-R TF.460-6 will become obsolete and services that currently transmit DUT1 will need to change the format to be transmitted.

To allow for an adequate period of time for legacy systems to adapt to the change in UTC, the leap second adjustments to UTC will remain effective allowing an adequate transition period, taking into account the constraints of different applications (e.g. all systems of Russian Federation including GLONASS require at least fifteen years for a complete update from the date of adoption).

UTC remains the only international reference time scale. No other time scale should be considered.

This proposal is coherent with the CGPM 2018 Resolution 2 that "UTC is the only recommended time scale for international reference and is the basis of civil time in most countries". It is constructed in an international cooperation with more than 80 timing institutes using transparent algorithms and is distributed in the form of the difference to the local realizations in each of the timing institutes.

No other existing time scale is suitable to fulfil the requirements as reference time scale. International Atomic Time TAI has no physical representation. It has to be understood as an intermediate step to construct UTC and it should not be considered as a potential future reference time scale. GNSS system times must not be considered as alternative to UTC; they are realized as GNSS internal parameters by their operators and any decision on their definition, realization, and dissemination is not taken by an international organization. Supporting documentation does not adhere to metrological practice.

4 Systems for dissemination of time signals

4.1 Introduction

The worldwide need for synchronization of local timing signals or synchronization of locally produced frequency signals with accepted national or international standards is ongoing, even growing in terms of required reliability and accuracy. Since the ITU and other scientific and technical organizations have recommended UTC as the appropriate international reference for time-and-frequency for most applications, it is relevant to briefly recall in this Report the various sources that exist for precise UTC information and the means for gaining convenient access to them.

Although the BIPM has the responsibility for establishing, maintaining, coordinating, and generally overseeing the UTC system, users throughout the world generally access local approximations to UTC through various national time-and-frequency dissemination services that are coordinated to be within close agreement with the international UTC time scale. The level of accuracy needed at the user's site is one of the more important factors in selecting a source of time-and-frequency reference signals from among several alternatives. Many different systems, techniques and services existing world-wide have been used successfully to satisfy a large variety of time and frequency requirements. They include both those dedicated for time and frequency needs and others that are designed primarily for other functions, such as navigation or communications.

In this section, radiocommunication services and those relying on other techniques have been compiled.

4.2 Radiocommunication services

As described in Recommendation ITU-R TF.374-6, the ITU has allocated the following specific frequencies for time-and-frequency dissemination: 20.0 ± 0.05 kHz; 2.5 ± 0.005 MHz; 5.0 ± 0.005 MHz; 10.0 ± 0.005 MHz; 15.0 ± 0.01 MHz; 20.0 ± 0.01 MHz; and 25.0 ± 0.01 MHz to the standard-frequency and time-signal service. The ITU Radio Regulations also include language which permits the use of specified portions of the 14-90 kHz region of the spectrum for time-and-frequency broadcasts on a secondary basis. In addition, several other frequencies were allocated to the Standard frequency and time signal-satellite service, but these have never been used for this purpose. Existing services are documented in Recommendation ITU-R TF.768-7 "Standard Frequency and Time Signals", with its annually updated Annex containing the detailed documentation being accessible from the ITU-R Study Group 7 website (see https://www.itu.int/oth/R0A08000007/en, accessed 2021-08-11). Recommendation ITU-R TF.583-6 (Time Codes) complements the information given by describing the coding of time information in the broadcast signals. Over the last decades, the number of dedicated radiocommunication services has declined and reception of signals from GNSS has taken over a big share.

The description of various dissemination methods for time and frequency applications is given in the following, with the restriction to frequency bands and services of actual use. The ITU Handbook "Satellite time and frequency transfer and dissemination" (2010) describes the use of satellite signals for time comparisons which is relevant in the context of the generation of UTC (see § 3.1.6) but not for dissemination to the public.

4.2.1 VLF broadcasts

VLF broadcasts in the 10-30 kHz range are useful primarily for frequency applications. Stable propagation characteristics and long-distance coverage make such signals useful for frequency comparisons at the 1×10^{-11} level or better. Operating services primarily exist in Russia, Japan and the United States of America.

4.2.2 LF broadcasts

Various dedicated services for time dissemination in the frequency range 40-162 kHz are operated in cooperation with institutes entrusted with the dissemination of legal time and serve millions of users. The most prominent services are WWVB in the United States, MSF in the United Kingdom, DCF77 in Germany, JJY in Japan, BPC and BPL in China, ALS162 in France and RTZ and RBU in Russia. See Recommendation ITU-R TF.583-6 "Time Codes" for an up-to-date compilation of the codes used for time dissemination. Signals from terrestrial navigation systems such as LORAN-C at 100 kHz still play an important role. In Western Europe, Japan, and the US most of the stations have been decommissioned. However, in other regions, LORAN-C stations are still in operation.

4.2.3 HF broadcasts

HF broadcast services make use of the internationally allocated frequencies for this purpose at 2.5, 5, 10, 15, 20 and 25 MHz. Other HF services use frequencies in other bands to reduce mutual interference. Such services provide modest accuracy performance but offer advantages in terms of wide geographical coverage, convenience of use and inexpensive user equipment.

4.2.4 Television broadcasts

The use of television signals for time dissemination used to be very effective and was common in some countries. With the development of digital broadcast, however, the properties of received signals no longer allow this use to be continued.

4.2.5 Global navigation systems (broadcast)

Recommendation ITU-R TF.374-6 explicitly refers to the frequency bands commonly used by the GNSS. On top of positioning, GNSS signals can be used for time determination and synchronization applications.

Signals from the satellites of the Global Positioning System (GPS) – the first GNSS – started to be used since the early 1980s for time comparisons. The primary purpose of all GNSS: GPS, GLONASS, Galileo, BeiDou is positioning and navigation. GNSS systems rely on precise timing, as the satellite ranges used to calculate position are derived from propagation time measurements of the signals transmitted from each satellite. The signals broadcast by GNSS satellites are derived from onboard atomic clocks (Caesium beam clocks, Rubidium gas cell clocks, passive Hydrogen masers) and contain timing and orbit information in their broadcasted navigation message. GNSS timing receivers have been developed, which use the received signal to discipline inbuilt oscillators to GNSS system time or, preferentially, to the prediction of UTC contained in the navigation message. They usually deliver a one-pulse-per-second (1 PPS) electrical signal or even a set of output signals (standard frequency signals, signals for telecommunication applications) that represent, with some uncertainty, either the GNSS system time or UTC as predicted in the GNSS navigation message. The use of such devices in calibration laboratories is very common. A large number of receivers is embedded in servers providing time (including time-of-day) information via IT-protocols like NTP or PTP (see below). There is an ongoing debate on how traceability to national or international standards can be established with reasonable effort using such instrumentation (Lombardi, 2016), (Matsakis et al, 2018), (Bauch et al., 2020).

Reception of GNSS signals suffers from delays introduced by the ionosphere and troposphere, and by multipath and receiver noise. A wide range of performances in terms of frequency instability and offset of the 1PPS output signal from UTC can be obtained, depending on the sophistication of the equipment and the efforts to determine the signal delays in the GNSS reception chain. Typical values achieved after several thousand seconds averaging are relative frequency instability and offset from nominal of 10-12 in frequency and time offset from UTC below 100 ns.

4.2.6 Augmentation systems for global navigation systems and regional navigation systems (broadcast)

Other satellite systems have been used for transmitting time signals in a one-way mode.

Satellite Based Augmentation Systems provide increased local navigational coverage and accuracy by transmitting corrections and a ranging signal to the existing GNSS. These are:

– Wide Area Augmentation System (WAAS) for GPS transmitting from an Inmarsat geostationary satellite (GEO) for increased coverage in the United States of America;
– European Geostationary Navigation Overlay Service (EGNOS) for Galileo transmitting from currently three GEO covering Europe;
– Multi-Functional Satellite Augmentation System (MSAS) transmitting augmentation signals to GPS from MSAS satellites with coverage of Japan and the surrounding Asian countries. A similar function has the Japanese Quasi-Zenith Satellite System (QZSS);
– Michibiki Satellite Augmentation System (MSAS) transmitting augmentation signals for GPS from the GEO of the Japanese Quasi-Zenith Satellite System (QZSS) with coverage of Japan and the surrounding Asian countries;
– System of Differential Corrections and Monitoring (SDCM) is a space-based augmentation system for GLONASS global navigation system increasing accuracy for users.

Navigation with Indian Constellation (NavIC), also known as Indian Regional Navigation Satellite System (IRNSS), is an independent regional navigation satellite system, designed to provide accurate position information in the Indian subcontinent.

Detailed descriptions of the above-mentioned systems are available in Recommendation ITU-R M.1787-3 “Description of systems and networks in the radionavigation-satellite service (space-to-Earth and space-to-space) and technical characteristics of transmitting space stations operating in the bands 1 164-1 215 MHz, 1 215-1 300 MHz and 1 559-1 610 MHz. Also, BeiDou (COMPASS), the Chinese GNSS, contains geo-stationary and geo-synchronous satellites as part of the space segment that serve regional augmentation purposes. The systems are also described in the ITU Handbook “Satellite time and frequency transfer and dissemination” (2010). The augmentation services have no particular role in time dissemination.

4.2.7 Meteorological-satellite

Between 1974 and 2004, the U.S. Geostationary Operational Environmental Satellite System (GOES) transmitted a time code referenced to the UTC(NIST) time scale. The time code was disseminated continuously from two geostationary satellites located normally at 75 degrees and 135 degrees West longitude. Satellite position data were also transmitted to users so that suitable automatic receivers can compute the signal path delay and correct their 1 Hz outputs accordingly. Specified time code accuracy as delivered to the user was 100 µs (Lombardi and Hanson, 2005).

4.2.8 Communications satellites (two-way mode)

Two-way satellite time and frequency transfer is nowadays instrumental for the realization of UTC (see § 3.1.6) but is not relevant in the context of time dissemination to the user. TWSTFT is described in Recommendation ITU-R TF.1153-4 – The Operational use of Two-Way Satellite Time and Frequency Transfer employing PN codes, and in the ITU Handbook “Satellite time and frequency transfer and dissemination” (2010).

4.3 Other dissemination systems

For completeness, a selection of time dissemination services outside the realm of the Radiocommunication sector are included. They all are based on UTC or legal times defined as UTC plus/minus integer numbers of hours.

4.3.1 Telephone time dissemination services

Several timing centres all over the world have established services designed to disseminate coded time information over telephone lines in an automated mode. Typically, computers and other automated systems are programmed to dial such services as needed, receive an ASCII time code and reset the local clock. Some systems are designed for automatic correction for the path delay involved through the telephone system. In such case, accuracies in the range of 1-10 ms are possible, but often the services are just used for ensuring TOD to a second. The available services are listed in the BIPM Annual Report on Time Activities which is accessible from the BIPM website. In 1990, several time-keeping institutes in Europe agreed upon a common format for time dissemination via the public telephone network in the frame of a EUROMET (what is now called EURAMET) project. This "European telephone time code" is till today being distributed by 8 institutes. The European telephone time code inter alia contains the DUT1 (the offset between UT1 and UTC with a resolution of 0.1 s) as defined in Recommendation ITU-R TF.460-6. The anticipated increase of DUT1 beyond 0.9 s will make a change of the coding necessary.

The European telephone time code inter alia contains the DUT1 (the offset between UT1 and UTC with a resolution of 0.1 s) by including a sign and an integer between 0 and 9. Thus, it does not follow the format of reporting DUT1 as defined in Recommendation ITU-R TF.460-6. The anticipated increase of DUT1 beyond 0.9 s will nevertheless make a change of the coding necessary. Other existing telephone time services will likely be affected as well.

4.3.2 Internet-based time dissemination services

Packet exchange using the NTP protocol (Mills et al., 2010) represents the most common method for synchronizing computer clocks and devices over the public Internet. The NTP-server operated at a site disseminating legal time is synchronized with a 1 PPS signal representing UTC(k) and the time-of-day information is received from any appropriate source. The master (also known as the time server) uses dedicated protocol packets to distribute time information to slave clocks (also known as clients). The process is initiated by a request from the client. Typically, the institute monitors the synchronization of its NTP appliance against services operated elsewhere. The time stamp that is used in the NTP format expresses the UTC time as the number of seconds and fractions of a second that have elapsed since 1 January 1900. Section 6.13 details the issues encountered in digital systems in general at the point in time when a leap second is introduced. The challenge in clock synchronization over packet-based networks is the variability of the network behavior. The accuracy of the clock synchronization service directly depends on the stability and the symmetry of the propagation delay in both directions between the master clock and the synchronized slave clock. Depending on the nature of the underlying network, time protocol packets can be subject to variable network latency or path asymmetry

Several institutes also provide a secured NTP time service. Such services usually apply the pre-shared key approach which is hardly scalable and thus cannot be offered to many customers. NTP's original security mechanisms became outdated and needed to be redesigned. On 1 October 2020, **RFC 8915: Network Time Security for the Network Time Protocol** was published by the Internet Engineering Task Force (IETF) (see https://www.internetsociety.org/issues/time-security/). NTP can now confirm the identity of the network clocks that are exchanging time information and protect the transmission of that time information across the network. No substantial degradation of the performance is noticeable when using NTS over the public Internet.

The IEEE 1588 Standard for "A Precision Clock Synchronization Protocol for Networked Measurement and Control Systems (PTP)" (IEEE, 2008) has been developed to provide better quality in-band clock synchronization in distributed measurement and control systems than NTP is able to achieve. Target has been groups of relatively stable components, locally networked (a few subnets), cooperating on a set of well-defined tasks. Sub-microsecond synchronization of real-time clocks in components of a networked distributed measurement and control system. IEEE 1588-2008 includes a *profile* concept defining PTP operating parameters and options. Several profiles have been defined for applications including telecommunications, electric power distribution and audio-visual.

4.3.3 Optical fibre-based time dissemination services

To circumvent the relatively large insertion losses particularly for high frequencies of standard RF cables, transport over optical fibres has become very popular and is expected to also reach the individual user, "fibre to the home". In the context of time distribution, the most relevant technology is based on the so-called White Rabbit standard (see https://ohwr.org/project/white-rabbit/wikis/home, accessed 2021-08-12). It was initially developed at CERN for distributing synchronization signals in the complex of accelerators. White Rabbit links over several hundred kilometres have been installed in the meantime, which allow transfer of standard frequency (10 MHz), PPS with uncertainty better than 1 ns, and time-of-day. Time-of-day information is usually obtained from an NTP-server operated near to the White Rabbit master clock. Other wide-spread usage of optical fibres in telecommunications and metrology are not concerned by the properties of the underlying reference time scale.

5 Use of UTC in radiocommunication services, technology, science and other applications

UTC has been recommended as the unique time scale for international reference and the basis of civil time by the General Conference on Weights and Measures (CGPM) already in 1975 and this has been lately confirmed in 2018. In compliance herewith, the use of UTC in the realm of ITU activities has been advocated in the Radio Regulations: "2.6: Whenever a specified time is used in international radiocommunication activities, UTC shall be applied, unless otherwise indicated, and it shall be presented as a four-digit group (0000-2359). The abbreviation UTC shall be used in all languages." This was also reflected in Recommendation ITU-R TF.460 (Standard Frequency and Time Signal Emission, 1970). This section describes systems that use UTC, starting with radiocommunication services, but expanding to other fields including technology and science.

5.1 Radiocommunication services

5.1.1 Radionavigation-satellite services

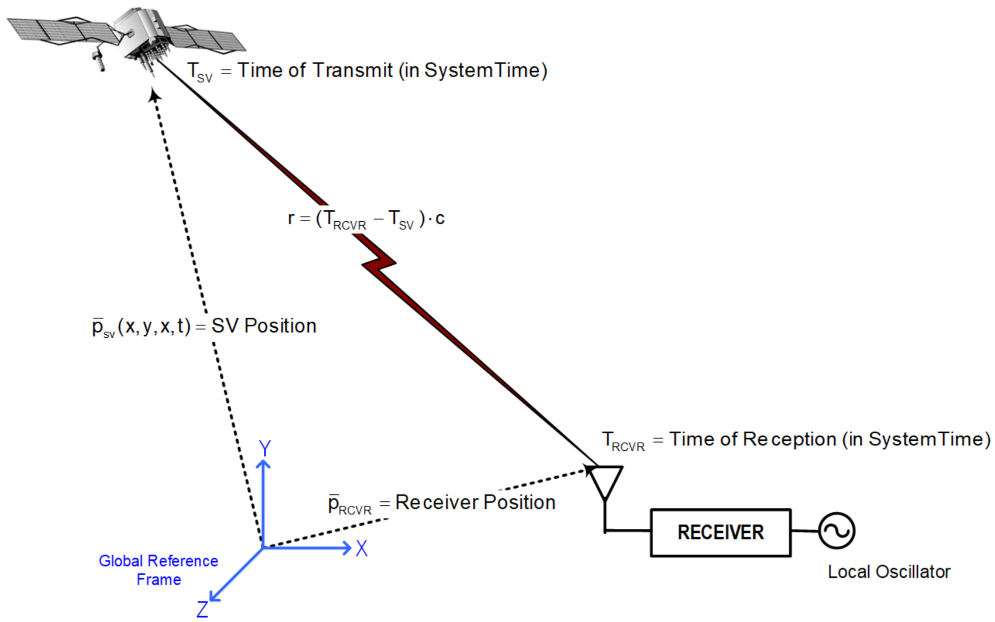
Radionavigation-satellite services (RNSS) require precise time to provide ranging measurements for positioning. For this purpose, they use internal system reference times: GPS Time, GLONASS Time, Galileo System Time, BeiDou System Time, all constructed from internal system clock ensembles. The precise time that has been made available by the RNSS systems has enabled a wide range of applications that take advantage of precise, easily available time. RNSS timing services have become critical to the infrastructure of the modern world since they are being used to provide precise timing to communications systems of all kinds from satellites to cell-phones, power-grid synchronization, financial transactions and monetary transfers, a wide variety of scientific applications, etc. Considering all operating and developing RNSS, there are well over 1 billion world-wide users.

It should be noted that the RNSS also disseminate time signals used for applications associated with safety (for example, usage of the navigation signals for aircraft landing approach).

RNSS have been developed and deployed that include atomic clocks as an integral part of their concept of operation. These RNSS have become the primary means of the precise and accurate dissemination of reference time standards. These systems are based on the concept of passive ranging which is to measure the time of transmission of special signals modulated to determine the precise distance between the transmitter and receiver. Consequently, these systems require precise synchronization of the satellites and ground network operating with them. The basic principle of passive ranging based on time of propagation measurements is illustrated in Fig. 12.

FIGURE 12

Passive ranging concept for RNSS



The distance or range between the satellite and user receiver (*r*) is determined by the precise measure of the time of propagation of a uniquely modulated ranging signal. To measure the time interval passively it is assumed that the satellite and receiver are synchronized adequately so that the range can be measured with sufficient precision for positioning purposes.

This synchronization is obtained through the use of a fourth equation (three for the coordinates X,Y,Z and one for the receiver time offset).

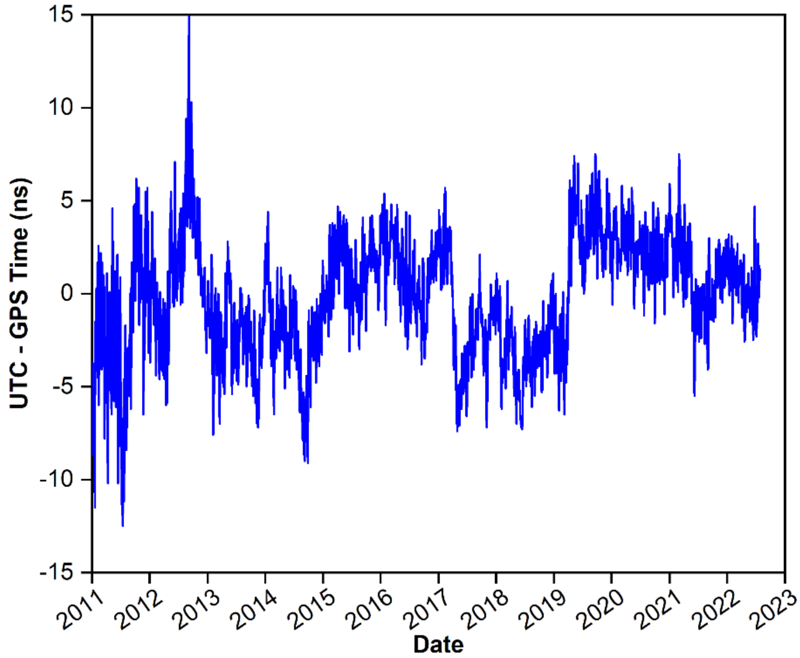
Finally, the receiver provides its position and its time offset with respect to the used GNSS time scale. Each GNSS broadcasts an estimation of the offset between its own time scale and a prediction of UTC (e.g. UTC(USNO) for GPS, UTC(SU) for GLONASS, etc.). Applying this correction allows the user to estimate its time offset with respect to a real-time representation of UTC.

In order to realize a common internal system time, such as GPS Time (GPST), satellite and tracking station clocks are used to determine a statistical formation of a uniform continuous system time. GPS Time is specified to be within 1 µs of UTC(USNO), excluding leap seconds. GPS Time can provide a broadcast time reference typically with a precision of ≤ 25 ns to UTC(USNO). However, in practice the precision can be 10 ns or better.

The epoch of GPS Time is midnight of 5-6 January 1980 UTC, i.e. 1980-01-06T00:00:19 TAI. Therefore, GPS Time is behind TAI by a constant value of 19 s. In mid-2022 GPS Time is ahead of UTC by 18 s as a consequence of the accumulated number of leap seconds in UTC since then. The comparison of GPS Time to UTC as determined by the BIPM is shown in Fig. 13.

FIGURE 13

UTC – GPST (modulo 1 s) from BIPM data



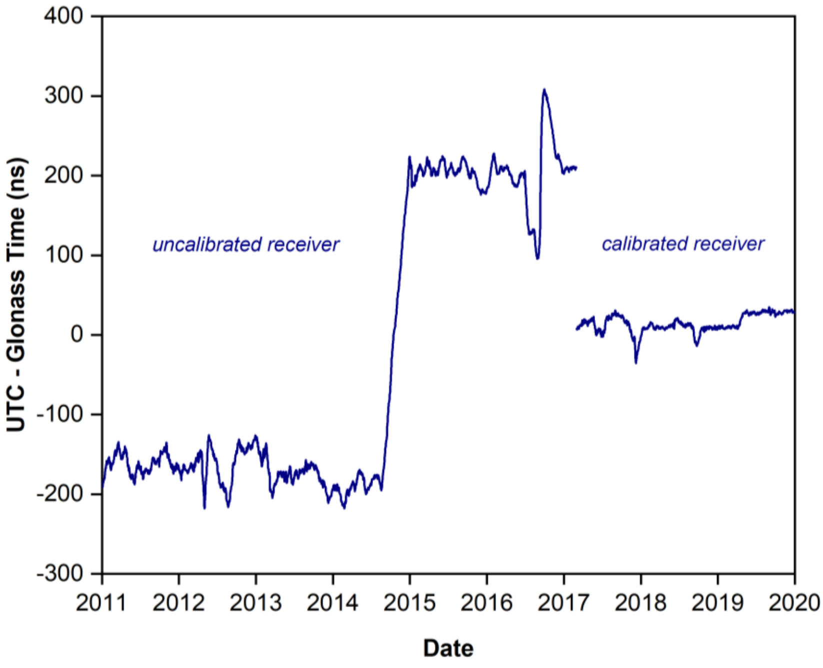
The E.U. Galileo Navigation Satellite System has adopted a uniform internal system time that does not contain leap seconds, known as Galileo System Time (GST) (*Galileo ICD*, 2010). GST also has a constant offset from TAI which is identical to that in GPS Time.

The BeiDou navigation satellite system Time (BDT) is adopted by the BeiDou system as the time reference. BDT adopts the SI second as the base unit and accumulates continuously without leap seconds. The start epoch of BDT is 00:00:00 on 1 January 2006 of UTC when 33 leap seconds had been introduced. This approach echoed the methodology of the GPS program but fixed BDT at a different epoch. BDT connects with UTC via UTC(NTSC), and the deviation of BDT to UTC is maintained within 50 nanoseconds (modulo 1 second). The leap second information is broadcast in the navigation message (BeiDou ICD, 2018).

A seeming necessity for a satellite navigation system is a uniform system of time that is continuous so that the navigation service need not be interrupted to reset clocks, but is capable of providing a realization of UTC to the system user receivers. The GLONASS system time scale (GLST) with a constant three-hour offset is maintained within 8 ns in relation to the Russian national time scale UTC(SU) and less than one second in relation to UT1. The information with respect to deviation of the GLONASS system time scale from UTC(SU) and deviation of UTC from UT1 is transmitted to the users by the corresponding correction in the satellite navigation signal (*GLONASS ICD*, 2008). GLST is corrected by an integer number of seconds simultaneously with UTC adjustment as determined by IERS. The comparison of GLST to UTC as determined by the BIPM is shown in Fig. 14.

FIGURE 14

UTC – GLONASS Time from BIPM data with 3-hour offset removed



The BIPM began monitoring GLONASS time based on the first GLONASS receiver developed at Leeds University (UK) by P. Daly at the end of 1980s. Since then, several laboratories successively monitored GLONASS time and provided data to the BIPM: Leeds University, Van Swinden Laboratorium (VSL) in the Netherlands with a VSL-3S Navigation receiver, and finally Astrogeodynamical Observatory (AOS) in Poland using Time Transfer System (TTS-3) and lastly TTS-4 receivers. Each change of receiver involved a differential delay calibration, so that up to the second decade of 2000 all GLONASS data for BIPM were referred to the P. Daly receiver. The situation at VNIIFTRI was quite similar, with a succession of receivers which started by the GLONASS receiver made by Russian Institute of Radionavigation and Time (RIRT) model A724 at the end of 1989, until the two last ones (TTS-3 and TTS-4) differentially calibrated with respect to the first one RIRT (A724). In the period 2013-2014 the absolute calibration of the TTS-4 VNIIFTRI receiver was performed for the first time. In consequence, GLONASS master station introduced the calibration correction into the GLONASS system time by a frequency steering. In 2015 VNIIFTRI carried the absolute calibration of a TTS-4 receiver from the BIPM. It was only in 2017 that the BIPM arranged the differential calibration of the AOS receiver relative to the calibrated BIPM one. After verification, the results were implemented in March 2017; from that time the values of the difference between the broadcasted UTC(SU)_GLONASS and GLONASS system time are calibrated.

GNSS internal time scales have been used by some users as time references for their applications as those internal system times are easily available and simple to apply for data collection and correlation. This has led to confusion among users, as the various system times differ significantly as well as being offset from UTC itself. For example, the International GNSS Service (IGS) uses GPS Time to time-tag the measurements of its products. These internal time scales should not be confused with the international time scale UTC as realized by UTC(k). Instead of referring directly to the GNSS times, users should preferably refer to information contained in the respective navigation message. Different GNSS rely on different UTC(k) and different algorithms to generate a prediction of the offset between this specific UTC(k) and the respective GNSS system time. The prediction is reported in the format of a time offset and a rate, both quantities specified as valid for a certain epoch. The receiver software can then calculate the predicted offset at the moment of reception of the signal. The predictions provide an accurate prediction of UTC itself as the UTC(k) scales involved all agree among each other and with UTC, typically well below 20 ns. In this sense, it is under consideration that GNSS service providers, with the help of time laboratories, improve the prediction of (UTC – GNSS Time), to enable the user to realize traceability to UTC through the broadcasted signal.

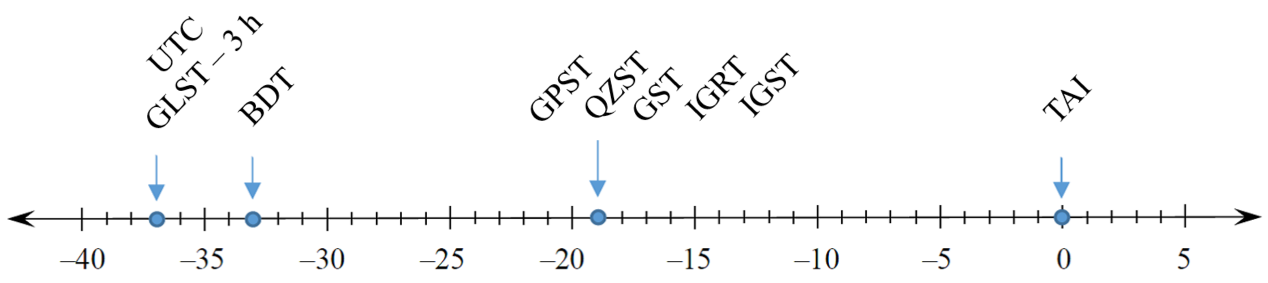
The IGS generates two-time scales to serve as the reference time for several of its main products. The IGS Rapid Time scale (IGRT) is generated daily in conjunction with the publication of the IGS rapid products and forms the reference time for the entirety of the IGS's rapid product. The same is true of the Final Time scale (IGST) with respect to the IGS's final products. The notation IGS(R)T is frequently used as a placeholder for either time scale (or both) – whatever is appropriate in context. More details about the evolution of the IGS's time scale and some of its features can be found in Senior et al., 2003, 2017 and Coleman and Beard 2019.

As the IGS's primary mission is the publication of GNSS data and computed products, it is most sensible that it incorporates leap seconds in a manner consistent with GNSS systems. Not all GNSS, however, have consistent architectures concerning leap seconds as explained before; to summarize, the GPS program chose to align its time scale with UTC at the start of its service on 6 January 1980. As a result, GPS Time contains the 19 leap seconds that were installed up to that time, but none of the leap seconds thereafter. The Galileo and QZSS programs chose to align their time scales (GST and QZST, respectively) with GPS Time for consistency between systems. The BeiDou program chose to align its time scale (BDT) with UTC at that start of its service, which came when 33 leap seconds existed. This approach echoed the methodology of the GPS program but put GPS Time and BDT at different times. Further, GLONASS has a system time (GLST) that incorporates all leap seconds but aligns its time scale with local time in Moscow which puts its time scale in alignment with the UTC realization UTC(SU) + 3 hours.

Since the IGS began its service with only GPS data in its core products (it is presently expending heavy effort to expand to multi-GNSS core products), the IGS's time scales are aligned to TAI – 19 s. It therefore has epoch timestamps that are consistent with GPST, GST and QZST. See Fig. 15 for a plot of the relationship between these time scales' alignments until the mid-2023 at least; the integral offsets between GNSS system times, except GLST, will change at the future leap second insertion.

FIGURE 15

Relationship between time scales as at the mid 2023; offsets are owed almost entirely to leap seconds. GLST is put to UTC(SU) + 3 hours to align the GLONASS system time with local Moscow Time



For the history of its service, the IGS's clock RINEX data records have been time-stamped in alignment with TAI – 19 s (consistent with GPS Time). As multi-GNSS files become more prevalent and possibly clock product files from Beidou or GLONASS are created, much more attention will be needed to ensure the correct system time ID is documented.

The continued introduction of leap seconds increases the discrepancy between UTC and most of the GNSS system times. Therefore, the IGS's clock product files record the number of leap seconds installed to UTC at the time of the data records contained in that file.

5.1.2 Radio astronomy service

The radio astronomy service (RAS) uses a local representation of UTC. It requires knowledge of the orientation of the Earth for pointing antennas. Currently the maximum difference between UT1 and UTC as determined by the IERS is limited to be within 0.9 s. With this maximum difference some users approximate UT1 by using UTC directly for pointing antennas. The precision with which the IERS determines UT1 – UTC is considerably better than 0.1 s as called for in Recommendation ITU-R TF.460-6. This value is published by the IERS and made available to users but is not used in broadcast systems due to the limitation in data size.

5.1.3 Mobile-satellite service

The systems of the mobile-satellite service (MSS) use a local representation of UTC. It is used in software and hardware levels as well to operate MSS systems especially in pointing the earth station antennas to non-geostationary satellites.

5.1.4 Fixed-satellite service

A local representation of UTC is used for operation of fixed-satellite service (FSS). For FSS and (broadcasting-satellite service) BSS, synchronization is required between components of these networks to permit the successful operation of scheduled transmissions. Given that operation centres are decentralized and automated this synchronization is critical for successful transmissions and to avoid the incorrect pointing of antennas used for these transmissions.

5.1.5 Broadcasting-satellite service

A local representation of UTC is used for operation of BSS. For BSS and FSS, synchronization is required between components of these networks to permit successful transmissions. Given that operation centres are decentralized and automated this synchronization is critical for successful transmissions and to avoid the incorrect pointing of antennas used for these transmissions.

5.1.6 Mobile service (MS)

The standard-frequency and time-signal service is used in International Mobile Telecommunications (IMT) systems for time synchronization. IMT sub-systems including base station use Long Term Evolution (LTE) technology and may synchronize by RNSS signals their billing systems for example. They also use a local representation of UTC in the operation of base stations that provide their telecommunications service. For billing purposes, the level of synchronization is to better than 1 s, for operations of base stations (5G) a synchronisation to UTC to better than 1.5 µs is required (Recommendation ITU-T G.8271/Y.1366). Tighter requirements are imposed for relative synchronization between neighbouring base stations.

5.1.7 Maritime mobile service, including global maritime distress and safety service (GMDSS), aeronautical mobile service and radiodetermination service

Maritime mobile service, including global maritime distress and safety service (GMDSS), aeronautical mobile service and radiodetermination service have systems that utilize a local representation of UTC.

5.1.8 Digital systems

Background information

Digital systems maintain time internally as the number of seconds and fraction of a second since some origin epoch. Typical origins are 0000 UTC on 1 January 1900 or 1 January 1970. The conversion to UTC and any additional conversion to the local time zone (including the offset for daylight saving time, if needed) are performed by the local system based on its internal configuration. These conversions are typically done by the application that requests the system time, so that different applications running on the same system may record different values for the time at some instant and may also use different formats to represent this value.

The origin times quoted above pre-date the current definition of UTC, which dates from 1972. Digital time stamps that reference instants earlier than 1972 are therefore unlikely to be consistent with the legal times of those eras. A calculation of a contemporary time stamp assumes that every day since the origin epoch consisted of exactly 86 400 seconds, and that every one of those seconds had the same interval as in the modern era.

Typical applications

Digital systems use the system time for three general types of applications:

1) The system time is used to apply a time stamp to some event. Individual time stamps may be needed for legal purposes, in which case traceability to national or international standards is important. Time stamps must also be able to validate causality and therefore must be consistent with the time ordering of events. The regulatory agencies in both the EU and the US require that time stamps traceable to UTC must be applied to financial transactions, and the forensic, after-the-fact, analyses of the time-ordering of transactions is of fundamental importance. The accuracy of the time stamps that are applied to financial and commercial applications vary somewhat depending on the details of the transaction and whether it is governed by the rules in the US or in the EU, but accuracy requirements at the millisecond level are not unusual.

2) The elapsed time measured by the system clock is used for internal accounting purposes, for profiling the time spent in executing some process, for acting as a "watch dog timer" to stop a process when the execution time of the process exceeds a maximum time limit, and for similar purposes. Processes that synchronize the local clock to a remote system (the Network Time protocol, for example) typically use the elapsed time as measured by the local system clock as a contribution to the method that is used to estimate the time delay between when a request for time is sent to a remote system and when the reply is received. The Network Time protocol (and similar wide-area synchronization methods) require that all of the participating servers and clients operate on a common time scale. The time scale must be monotonic and smoothly varying. Since the protocol works with time differences, the use of the UTC time scale is desirable in practice and to satisfy other requirements, but is not required in principle.

3) The system clock is used to schedule an operation, such as to start of a process at a specific time. The time scale that supports this application must be monotonic and have unique time stamps. This requirement is particularly important for processes that operate in a distributed environment or that access data that are stored at multiple locations. The processes that run and update the data must share a common time scale so the data are consistent across the entire network.

4) Various applications depend on the frequency of UTC or on measurements of time differences at different locations. Examples are the control of the frequency of the electrical power grid, the location of faults in long-distance transmission systems, and the synchronization of transmission systems that use time-division multiplexing to share a single communications channel among multiple users. The time of arrival of a seismic signal at several locations is used to determine the location of a seismic event and is another example of an application that depends on this requirement.

To satisfy these requirements, the system time must be monotonic and smoothly varying. If the application requires traceability to national or international standards, then the system time must have a known and constant relationship to UTC. To support post-processed applications, the relationship between the system time and UTC must also be known for any historical data of interest.

In general, systems do not include any meta-data with the system time, so that the parameters that convert from the internal representation to UTC (in any format) must be known by the process that performs the conversion. This imposes a significant requirement on processes that exchange time stamps between different systems. The time scale and the implicit origin time of the data exchange must be known in some way, and any differences in the internal representation or in the algorithm that converts the internal representation to the output datum must either be hidden or be transmitted as meta-data between systems. The protocols that are commonly used to exchange time information (the Network Time Protocol, or the older TIME format, as examples) generally adopt the first alternative – the transmitted datum has an implied origin time and scale unit that are not transmitted but are treated as universal constants of the protocol.

Leap seconds and UTC

Under normal circumstances, the last second of a UTC day has a time stamp, in format hh:mm:ss, of 23:59:59 UTC, and the next second is 00:00:00 UTC of the next day. When a positive leap second is required, it is added as the last second of the day, usually on the last day of June or December. The official name of the leap second is 23:59:60, so that the last minute of a leap-second day has 61 seconds, numbered 0 to 60.

Digital representation of leap seconds

Although the name of the leap second is unambiguous when a time is expressed in the hh:mm:ss format, the occurrence of a leap second is not included in calculations of time interval or elapsed time. The elapsed time that is calculated by subtracting two-time stamps will not agree with the physical time that has elapsed if the time interval in question crosses a leap second. (This is exactly equivalent to ignoring the number of leap days in determining a person’s birthday and chronological age.) This problem exists in principle no matter what format is used to express a time stamp but is particularly difficult when a time stamp is expressed as the number of seconds since some epoch, as is common in digital systems. The relationship between time expressed as the number of seconds since some epoch and time expressed in the hh:mm:ss format has a discontinuity at every leap second once that leap second has occurred. There is no provision in the time formats to account for previous leap seconds – they are effectively “forgotten” once they have occurred. In order to maintain compatibility with the hh:mm:ss format, a binary representation of any time must incorporate some mechanism for addressing this discontinuity.

5.1.9 Time-stamping service

Time-stamping services (TSS) use a Time of Day (TOD) information according to UTC. In TSS, the Time-Stamping Authority (TSA) clock used to create time-stamp tokens (TSTs) is required to be synchronized with UTC within the declared accuracy and shall be managed so as to guarantee the correctness of the time parameter included in the TST. The Time-Assessment Authority (TAA) certifies the traceability of the time reference of the TSA to the time scale of UTC(k) provided by a timing centre and may, optionally, distribute time information to the TSA. As for the time-stamping services, ISO/IEC 18014 standard shall be referred to. As for the functions of the TAA, Recommendation ITU-R TF.1876 shall be referred to.

5.1.10 Financial services

High frequency trading has made the financial market extremely dependent on clock synchronization. The (European) regulations require that events be recorded using only synchronized clocks traceable to UTC.

The Markets in Financial Instruments Directive 2004/39/EC (MiFID) is a European Union law that provides harmonised regulation for investment services across the member states of the European Economic Area. Member states shall require that all trading venues and their members or participants synchronise the business clocks they use to record the date and time of any reportable event in accordance with international standards. The relevant regulation states that ‘Operators of Trading Venues and their members or participants should establish a system of traceability to UTC’. This includes ensuring that their systems operate within the granularity and a maximum tolerated divergence from UTC as per Commission Delegated Regulation (EU) 2017/574. The maximum tolerated divergence from UTC ranges from 1 ms to 100 µs, and the granularity of the time stamps should be in the range 1 ms to 1 µs or better.

Leap seconds should be handled in accordance with Recommendation ITU-R TF.460-6.

5.1.11 Maritime navigation

IMO makes extensive use of UTC in its requirements and will continue to do so in future.

Celestial navigation is a requirement of the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers, 1978, as amended and is important to the maritime community, which requires time based on Earth rotation. Inertial navigation, which is currently used by naval ships and has been introduced on merchant ships, requires an accurate time reference.

5.2 Time metrology and traceability

Navigation satellites provide a means of time dissemination, and together with communication satellites they are the tools used in time metrology for time scale comparison.

The technique of common-view consists on observing the same GNSS satellite from two different timing sites at precisely the same time. Subtracting the results from the two sites eliminates effects of the satellite clock and at least partially compensates for ephemeris errors. Intentional degradation of the satellite signals may or may not degrade the common-view time comparisons, depending on how it is implemented. Time comparison uncertainties of better than 20 ns for widely separated sites are routinely possible. This approach offers higher accuracy than the direct method but requires special coordination arrangements among the sites being compared. To achieve the 10^{-16} instability, integration times up to ten days are required. In the absence of intentional degradation of the satellite signals, the availability of clock and ephemeris parameters through the IGS allows time comparisons using all satellites in view, with a substantial reduction in uncertainty. Calibration of GNSS equipment is necessary for the accuracy time comparisons. International campaigns of calibration allow today to achieve few-nanosecond uncertainty.

At present, the two-way exchange of timing signals through communication satellites known as Two-Way Satellite Time and Frequency Transfer (TWSTFT) offers the most accurate satellite technique for comparing remote timing sites. Much experience has been gained throughout the world with this technique and an increasing number of timing centres are using, or preparing to use, this technique for operational international time transfers to an uncertainty level that approaches 1 ns. Advantages include the high accuracy capability and the availability of many suitable communication satellites in all regions of the world. Disadvantages include the need for users to both transmit and receive timing signals and the relatively high equipment and operational costs. At the highest accuracy levels, the careful calibration of ground-station equipment delays is a necessary requirement. Specialized time-transfer (analogue and, more recently, digital) modems, optimized for high accuracy and stability, are used for timing applications. In the last years the development and operation of Software-Defined Radio (SDR) receivers substantially improved the statistical uncertainty of two-way time transfer, and the overall uncertainty in the time link calibration. The SDR technique achieves sub-10^{-16} instability level below ten days.

Metrological traceability is defined as property of measurement result whereby the result can be related to a reference through a documented unbroken chain of calibrations, each contributing to the measurement uncertainty.

There are various ways to demonstrate conformity to metrological traceability:

a) Calibration and measurement capabilities provided by national metrology institutes and designated institutes that have been subject to suitable peer-review processes. Such peer-review is conducted under the International Committee for Weights and Measures Mutual Recognition Arrangement (CIPM MRA).

b) Calibration and measurement capabilities (CMCs) that have been accredited by an accreditation body subject to the ILAC (International Laboratory Accreditation Cooperation) Arrangement or to Regional Arrangements recognized by ILAC have demonstrated metrological traceability.

c) More specifically in Time metrology, establishing traceability route to the SI second should be performed by participating to the monthly key comparison CCTF-K001.UTC piloted by the BIPM and published in the BIPM KCDB (Key Comparison Data Base) or via another national metrology institute which participates to the key comparison CCTF-K001.UTC having relevant CMCs with appropriate uncertainty published in the BIPM KCDB.

The Joint BIPM, OIML (International Organization of Legal Metrology), ILAC and ISO Declaration on Metrological Traceability provides specific guidance when there is a need to demonstrate international acceptability of the metrological traceability chain.

5.3 Astronomy

The astronomical community has many diverse specialties and expertise, but may be generally described by the following categories:

– The majority of astronomers today – including the majority of observing astronomers are experts in astrophysics, cosmology, theoretical astronomy, stellar evolution, galactic structure, extragalactic objects, etc. They are generally not concerned or knowledgeable about fundamental astronomy, including time scales and reference systems.

– A specialized group of astronomers are primarily interested in Earth orientation and timekeeping. They participate in IAU Division A, Fundamental Astronomy, and in particular in its commissions A1 (Astrometry), A2 (Rotation of the Earth) and A3 (Fundamental Standards).

Various organizations provide ephemeris services for different applications and users. These services publish tables of events in annual printed volumes and also electronic ephemerides via their web sites. In all cases the computation is based on prediction algorithms. Electronic ephemerides may be calculated in different time scales, such as TT, UT (assimilated to UT1) and UTC. For applications such as observing an object from the Earth’s surface using its altitude/azimuth coordinates, or to calculating rising and setting times, both the wall-clock time of the event, (determined) expressed in UTC, as well as UT1 are involved.

5.4 Geodesy

Geodetic techniques have experienced in the last few decades a great revolution and a technological breakthrough in terms of precision, accuracy, accessibility and availability. The consequence has been an increase of applications in terms of research of any kind, fundamental physics and link with General Relativity, realization of space and time reference systems, better knowledge of the terrestrial gravity field, plate tectonics, deformation of the terrestrial crust, seismology, glaciology, sea level, and others. A similar impact happened on societal applications such as navigation on land, sea and in the air, the dissemination of time, and meteorology. This is particularly true for the four operational GNSS: GPS, GLONASS, BeiDou and Galileo (this last one essentially a civil system).

The geodetic community is involved in time scale issues at two levels, as:

– users of these time scales both for time-tag of measurements and time-variable in models;
– providers, considering the key role of space geodesy in the realization of these scales (especially for relativistic corrections).

For many people, including geoscientists, there is an apparent multiplicity of existing time scales, such as Barycentric Dynamical Time (TDB), Terrestrial Dynamical Time (TDT), Geocentric Coordinate Time (TCG), Terrestrial Time (TT), International Atomic Time (TAI), UTC, GPS Time, and so forth. These time scales refer to different definitions or physical realizations and require a clear understanding of their respective roles and relations.

As fundamental reference, the geodetic community considers that the adoption of a unique preferred international time scale is important, both from a theoretical and operational point of view. In a manner similar to the terrestrial reference system for which the International Terrestrial Reference System (ITRS) was adopted, it would be highly desirable that this choice would be the same as that of other communities.

At this stage, UTC can be considered as a possible choice without any changes in the adopted agreements. The geodetic requirement for knowledge of the Earth Rotation Angle (ERA) is met by the availability of estimates of UT1 – UTC accessible through the Internet and it is therefore strongly recommended to use them to benefit the precision of modern geodetic techniques especially at the millimetre level.

– From a theoretical point of view, the definitions of time scales in the IERS conventions are consistent with several IAU and IUGG resolutions. In this context, TCG and TT are the main time scales for Earth system modeling. The ephemeris of the solar system bodies is now expressed in TT and widely available.
– From an operational point of view, UTC predictions are accessible through various channels such as terrestrial or space-based radio signals for geodetic applications.

5.5 Radio sciences

Radio sciences play a role in the advancement of telecommunications science in general. UT1 is necessary for applications in the space industry, Earth-based observations, for the transformation between the fixed and rotating reference systems; for these applications, access to UT1 is needed.

5.6 Meteorology

Some radiosonde receive systems, operating in the meteorological aids service, use UTC. The software sets the time on the receive system computer to UTC. The time is checked from RNSS satellites and the observation time is adjusted, including applying any required time correction.

The data transmitted from the in-flight metaid to the receiver ground station, for processing and production of data messages and reports, is time stamped with RNSS time.

UTC is used in the global transmission of processed data messages and reports by default. Every sounding is referred to the standard time of meteorological observations (0000, 0600, 1200 and 1800 UTC). The rounding is done based on the UTC to the nearest standard time. The UTC is used as a timestamp for the sounding (time of launch) in format HH:mm:ss.fff. The observations originating from other systems, e.g. surface weather stations, are also referred to the standard time.

If any changes to the UTC are made, e.g. removal of the leap second, the software for some metaid systems will need to be updated, and distributed to the system users. The standard update cycle of the software is six months thus the preparation for software updates should be prepared at least one year before the change is planned to be effective.

5.7 IT and Industry 4.0

The global economy is strongly dependent on GNSS, which provides the UTC reference to all modern critical infrastructures, such as distributed smart grids, telecom 5G, financial markets and broadcasting. Moreover, the observed strong migration of smaller IT and Industry 4.0 (Operational Technology, OT) systems to CLOUD makes it a 5th critical infrastructure.

6 Impact of a possible change of UTC to a continuous time scale in radiocommunication services, technology, science and other applications

The effects of a possible change of UTC to a continuous time scale are outlined below.

For legacy systems relying on the use of leap seconds in UTC it may be necessary to change or update the software and, in some cases, also the hardware while backward compatibility cannot be ensured in this case. Some technical documents will need to be amended to reflect the change of UTC.

Without further insertion of leap seconds the difference between UTC and UT1 will go beyond the currently established maximum offset of 0.9 s and increasing the limit of UT1 – UTC will make the procedure of UTC correction a rare event.

Additional effects of a possible change in the definition of UTC by stopping the insertion of leap seconds are outlined below for various services.

6.1 Impact on radionavigation-satellite service

In case of UTC change, some RNSS systems would require update/change. However, in some cases the navigation equipment cannot be modernized in its operational lifetime. Spaceborne receivers are an extreme example.

The necessary updates and changes will lead to high financial expenditures in some systems and also require update of all authorized technical documents, carrying out of complete cycle of retests and recertification of these systems and objects (for example, aircrafts, launch vehicles, etc.) Thus taking into account a wide usage of RNSS systems all over the world and a large amount of the current equipment employing various synchronization procedures, negative effects due to UTC change are possible for the operation of some existing services and systems of the RNSS.

Considering that navigation information is basic for building such high-tech areas as a smart city, automation in the agricultural and in the construction sectors and other areas, underestimating all the consequences in the event of a change of UTC could lead to potential economic effects.

6.1.1 Advantages and disadvantages of using the current UTC

An advantage of continuing the current UTC usage ensures backward compatibility for the current systems without update or replacement. In addition, the update of the authorized technical documentation with the current UTC definition is not required.

A disadvantage associated with the usage of the current UTC is the need for adjustment of UTC by the occasional insertion or deletion of leap seconds.

Complex systems such as the GNSS use preferably a continuous internal system time. These internal times are constrained to keep close to UTC (modulo an integer number of seconds). Only GLONASS made the choice of having an internal system time that implements the leap seconds in order to follow UTC, in agreement with the international standards (or more precisely UTC + 3 h).

In the 1990s, issues with GLONASS positioning were reported (Misra, *et al*., 1993; Misra, *et al.*, 1996b) at the introduction of the leap second of 1 July 1992, 1 July 1993 and 1 January 1996. More recently, it is still often reported that GLONASS users may experience issues with GLONASS signal tracking after the implementation of a leap second, and sometimes up to 1 h after the event, e.g. (EOS, 2017), (Spatial Technologies, 2016). For some GLONASS receivers, if they are used after the leap second, they will have trouble tracking GLONASS signals until a new almanac is downloaded, which can take up to a few minutes. Non-assisted acquisition of GLONASS signals is also impaired during the implementation of a leap second (GLONASS ICD, 2016).

The inconvenience and cost of implementing leap seconds is circumvented by the other GNSS which decided to use a continuous system time. However, each GNSS has a different choice concerning the epoch (except GPS and Galileo which have the same). As GNSS system times are widely available to users, this may create confusion. When a user does not apply the correction to approximate to UTC and directly uses a GNSS system time, offsets of several seconds will be present, and will change with time, which may lead to unexpected issues in various sectors. Moreover, for the interoperability of GNSS, this time varying offset of several seconds can create an issue, while in case of continuous UTC the offset will remain constant.

6.1.2 Advantages and disadvantages of using a possible continuous UTC

The advantage is that stopping the insertion of leap seconds in UTC eliminates software, protocols, and coordination necessary to occasionally accommodate leap seconds in systems and provides a continuous UTC that improves continuity and reliability.

A continuous reference time should be an adequate reference to the internal time base for many GNSS systems. Differences of a few ns would be expected among them (instead of several seconds), avoiding the possible issues mentioned above. Moreover, this situation might help interoperability between systems.

Each GNSS has made a different choice concerning the epoch (except GPS and Galileo which have the same). So, after stopping leap seconds, all GNSS system times will have constant offsets, this may continue to create confusion, but at least theses offsets will remain constant. To take complete advantage of a continuous UTC and avoid the risk of confusion among time scales, the GNSS could consider the alignment of their system times to UTC.

With respect to disadvantages, it should be pointed out that the time difference between UTC without further insertion or exclusion of additional seconds and UT1 will increase by more than the current limit of 0.9 s.

This issue affects some space RNSS segment, because the message structure transmitted by the systems has finite register capacity. Since the DUT1 correction value will be continuously changing, it might not be registered correctly. Therefore it will be necessary to change or update the software and possibly the hardware.

Also, this issue would affect earth RNSS segment that uses UTC as an approximation of UT1 or that uses the difference UT1-UTC for a finer approximation of UT1. Therefore, it will be necessary to change or update the software and, in some cases, also the hardware while backward compatibility cannot be ensured in this case. Failure of these systems and some new systems relying on UT1 caused by legacy software or human factors could occur. Technical documentation will need to be amended to reflect the change in the utilization of UTC.

This can be an issue for the GNSS transmitting the value of UT1-UTC in their navigation message and having at disposal a limited number of bits allowing only a value smaller than 0.9 s. This is the case of GLONASS which should undergo an update.

According to the available information, GLONASS is undergoing a major upgrade and the next generation of satellites GLONASS K2 will allow to transmit a value of DUT1 up to ±256 seconds. The full constellation is expected not earlier than year 2030. Further to the upgrade of the satellites, an upgrade of ground-based satellite complex and equipment of radio navigation stations/receivers is required. The average lifetime of this equipment is estimated to 10 to 15 years.

GPS and QZSS have already enough bits in the navigation message to accommodate a value of DUT1 of 64 s, while Galileo is not transmitting DUT1. For these systems there is no impact at least for about the next 100 years.

6.1.3 Measures and time period required for radionavigation-satellite service to implement changes of UTC

The duration of the required transition time for those affected RNSS systems is at least 15 years, based on typical satellite lifetimes. However, the actual duration of the required transition time period will depend on the financial, legal and arrangement consequences which can significantly extend this period (no less than 15 years) and will be dependent upon the Administration.

6.2 Impact on mobile-satellite service, fixed-satellite service and broadcasting-satellite service

In case of UTC change, software and hardware update and/or upgrade for MSS, FSS and BSS systems will be required.

MSS, FSS and BSS satellite systems are "active" systems. In accordance with the Radio Regulations, space station on board geostationary satellites shall have capabilities of maintaining their positions within ± 0.1° of the longitude of their nominal positions for FSS/ BSS satellites, and within ±0.5° for MSS satellites if there is no overlapping with FSS/BSS frequency bands (if there is overlapping of MSS with FSS/BSS frequency bands, then ±0.1° is applied). The mis-pointing of the antennas of such satellite systems could violate the electromagnetic compatibility conditions and it could result in unacceptable interference that would affect other satellite systems and other radio services. Taking into account intense and wide usage of satellite systems services all over the world and a large amount of the current equipment with various synchronization procedures, the negative impact due to UTC change to the operation of existing services and systems of MSS, FSS and BSS is possible.

6.2.1 Advantages and disadvantages of using the current UTC

In relation to advantages, the use of the current UTC definition permits backward compatibility principle for the current MSS, FSS and BSS systems without update and replacement. Updating technical documentation with the current UTC definition as described in Recommendation ITU-R TF.460-6 is not required. The disadvantage of the current UTC is the need for adjustment of UTC by the non-periodical insertion or deletion of leap seconds with all the associated risks and consequences.

6.2.2 Advantages and disadvantages of using a possible continuous UTC

The advantage of it is that suppression of the use of leap seconds in UTC eliminates software, protocols, and coordination necessary to accommodate leap seconds in systems.

With respect to disadvantages, it should be pointed out that the time difference between UTC without further insertion or exclusion of additional seconds and UT1 will increase by more than the current limit of 0.9 s.

This issue would affect two categories of systems; one that uses UTC as an approximation of UT1, and the second that uses the difference UT1 - UTC for a finer approximation of UT1. For legacy systems relying on the use of leap seconds in UTC it will be necessary to change or update the software and, in some cases, also the hardware while backward compatibility cannot be ensured in this case. Failure of these systems and some new systems relying on UT1 caused by inadequate software or human factors could increase. Some technical documents will need to be amended to reflect the change in the definition of UTC.

6.2.3 Measures and time period required for mobile-satellite service, fixed-satellite service and broadcasting-satellite service to implement changes of UTC

From the technical point of view the duration of the required transition time period for MSS, FSS and BSS satellite systems is uncertain at this time. However, the actual duration of the required transition time period would depend on the financial, legal and arrangement consequences which could be as long as the lifetime of operating systems and would likely be different for each administration.

6.3 Impact on the mobile service

Taking into account that the International Mobile Telecommunications (IMT) systems are widely used all over the world and there is a large amount of the current equipment with various synchronization procedures, there may be some undetermined consequences to the operation of existing services and systems of IMT in case of UTC change, depending on the implementation of synchronisation procedure.

6.3.1 Advantages and disadvantages of using the current UTC

Some minor impacts to the existing IMT systems may be experienced. For example, insertion of leap second could cause some errors of per-second billing. However, IMT system operators resolve those problems after the leap second has occurred.

With respect to Long-Term Evolution (LTE) and Time Division Duplex (TDD) it should be noted, that the time distribution defined by ITU-T for these specific IMT networks is based on the IEEE 1588 precision time protocol (PTP); which is not directly based on UTC. However, there may be IMT network clock sources that make use the RNSS as reference.

6.3.2 Advantages and disadvantages of using a possible continuous UTC

In the IMT context is required to coordinate the transmission of the start of the radio frames between adjacent base stations, and UTC is the preferred common reference, according to information provided by ITU-T SG15/Q13 (Document 7A/38). Information carried by leap seconds is irrelevant. In practice for network synchronization, continuous timescales are important, and in fact current solutions avoid the impact due to leap seconds, by making use of timescales or time information that do not include leap seconds such as the PTP timescale. According to IEEE 1588 the PTP time scale is distributed as the number of TAI seconds since 01.01.1970 combined with a field containing the difference between UTC and TAI.

In conclusion, defining for the future a continuous UTC without additional leap seconds can be considered beneficial in the telecommunication context as it could simplify related specifications and reduce risks on some implementations. There still may be some impacts on IMT network clock sources that may use the RNSS as reference.

6.3.3 Measures and time period required for mobile service to implement changes of UTC

Currently there is no information available on the exact amount of transition time required for IMT systems in case of a possible change of UTC.

It is expected that the adoption of a continuous UTC will not raise issues of practical backward compatibility on telecom applications. No particular time is needed to adapt to the future new situation.

6.4 Impact on the radio astronomy service

In case of a change in UTC that would result in the difference between UT1 and UTC to become larger than 0.9 s, some modifications might be necessary in some astrodynamical software used in pointing telescopes to track celestial objects. Tracking of radio astronomical sources from spacecraft is also required and presents a more complicated antennas pointing situation.

6.4.1 Advantages and disadvantages of using the current UTC

In relation to advantages of the current UTC usage it allows to ensure backward compatibility principle for the current systems without update and replacement. In addition, the update of the authorized technical documentation with the current UTC definition as described in Recommendation ITU-R TF.460-6 is not required.

In relation to disadvantages associated with the usage of the current UTC the need for adjustment of UTC by the non-periodical insertion of leap seconds is continued with all the associated risks and consequences. The manual insertion of leap-seconds at infrequent intervals has created issues at radio telescopes, especially for precise timing observations such as pulsars.

6.4.2 Advantages and disadvantages of using a possible continuous UTC

The advantage of it is that stopping leap second insertions in UTC eliminates software, protocols, and coordination necessary to accommodate future leap seconds in systems. Change to a continuous time scale will simplify operations as no leap second insertion will be required.

With respect to disadvantages, it should be pointed out that the time difference between UTC without further insertion or excluding of additional seconds and UT1 will increase by more than the current limit of 0.9 s. In addition, for legacy systems relying on the use of leap seconds in UTC it will be necessary to change or update the software and, in some cases, also the hardware operating these systems (backward compatibility is not ensured). Some technical documents will need to be amended to reflect the change in the definition of UTC.

In case of a change in UTC that would result in the difference between UT1 and UTC to become larger than 0.9 s, some modifications might be necessary in some astrodynamical software used in pointing telescopes to track celestial objects. Tracking of radio astronomical sources from spacecraft is also required and presents a more complicated antennas pointing situation. Consequently, some astronomers are concerned by a possible change in UTC since it may require financial expenditures and also updates of technical documentation. However, there is general agreement that, should a transition to a uniform continuous time scale be agreed, sufficient time should be allowed for system modifications to be made before implementing any changes.

6.4.3 Measures and time period required for radio astronomy service to implement changes of UTC

Currently there is no information available on the duration of the required transition time period. The transition duration is dependent on the actual systems used and the changes proposed.

However, there is general agreement that, should a transition to a uniform continuous time scale be agreed, sufficient time should be allowed for system modifications to be made before implementing any changes.

6.5 Impact on the maritime mobile service, including global maritime distress and safety service (GMDSS), aeronautical mobile service and radiodetermination service

Taking into account that the systems in the maritime mobile service, including GMDSS, aeronautical mobile service and radiodetermination service are widely used all over the world and that there are various synchronization procedures, the negative consequences due to UTC change are possible to the operation of the above mentioned radio services. In addition it should be noted that these systems use the navigation signals received from the RNSS that would be affected by a UTC change.

6.5.1 Advantages and disadvantages of using the current UTC

In relation to advantages, the use of the current UTC definition permits backward compatibility principle for the current MSS systems without update and replacement. Updating technical documentation with the current UTC definition as described in Recommendation ITU-R TF.460-6 is not required. The disadvantage of the current UTC is the need for adjustment of UTC by the non-periodical insertion or deletion of leap seconds with all the associated risks and consequences.

6.5.2 Advantages and disadvantages of using a possible continuous UTC

The advantage of it is that suppression of the use of leap seconds in UTC eliminates software, protocols, and coordination necessary to accommodate leap seconds in systems.

With respect to disadvantages it should be pointed out that the time difference between UTC without further insertion or exclusion of additional seconds and UT1 will increase by more than the current limit of 0.9 s.

This issue would affect two categories of systems; one that uses UTC as an approximation of UT1, and the second that uses the difference UT1 - UTC for a finer approximation of UT1. For legacy systems relying on the use of leap seconds in UTC it will be necessary to change or update the software and, in some cases, also the hardware while backward compatibility cannot be ensured in this case. Failure of these systems and some new systems relying on UT1 caused by inadequate software or human factors could increase. Some technical documents will need to be amended to reflect the change in the definition of UTC.

6.5.3 Measures and time period required for maritime mobile service to implement changes of UTC

From the technical viewpoint the duration of the transitional period for the systems in the maritime mobile service, including GMDSS, aeronautical mobile service and radiodetermination service is not less than ten years. However the actual duration of the transitional period will depend on the financial, legal and arrangement consequences which can significantly extend this period (more than ten years) and will be individual for each administration.

6.6 Impact on Maritime navigation

IMO makes extensive use of UTC in its requirements and will continue to do so in future. IMO recognizes that there are advantages and disadvantages of the various methods and recommends Administrations consider that the issue goes beyond maritime matters (IMO Document WRC15/13, 24 June 2015).

Making use of a terrestrial system in case of unavailability of GNSS would not present insurmountable problems if the systems have the same time reference and it is continuous. The difficulty is to find a common reference time. The temporal coordination of systems is a pre-requisite, no matter on the chosen reference and whether it is continuous or not. In general, these systems determine the distances by measuring the time of a signal to join two points; the time reference is irrelevant, provided that it is continuous, that it is common to all, and that the position of the emitter is known at the moment of the signal emission.

6.6.1 Advantages and disadvantages of using the current UTC

Some manufacturers have reported difficulties in updating equipment when having to take into account the leap seconds (IMO Document WRC15/13, 24 June 2015).

Systems used for maritime navigation risk certain disruptions at leap second introductions

Inertial navigation has to use the same time reference as GNSS, and it should be preferably continuous. The current UTC with discontinuities at leap second insertions obliges to apply steps simultaneously to all systems involved, making the process complex and risky.

In general terms, and concerning all applications in maritime navigation the current practice of maintaining UTC close to UT1 provoked an absence of harmonization of the method to insert a leap second in the navigation systems and in the user's systems of time, representing a negative consequence of the present UTC.

6.6.2 Advantages and disadvantages of using a possible continuous UTC

The advantage of eliminating the leap second is that it would remove the cost and disruption involved in adjusting equipment. The disadvantage would be that the definition of UTC would change which might have regulatory consequences (IMO Document WRC15/13, 24 June 2015).

For inertial navigation a continuous UTC would be beneficial. This would provide a continuous reference compatible with GNSS and will avoid possible systems disruptions arising from steps. Using a time reference not constrained to be close to rotational time does not seem to have any impact.

In general, stopping the insertion of leap seconds in UTC will eliminate the risks of lack of synchronization in navigation.

However, a continuous UTC does not address the problem that the GNSS system times have different offsets with respect to UTC, but these different offsets will remain constant.

For legacy systems relying on the use of leap seconds in UTC it will be necessary to change or update the software and, in some cases, also the hardware while backward compatibility cannot be ensured in this case. Failure of these systems and some new systems relying on UT1 caused by inadequate software or human factors could increase.

Some technical documents will need to be amended to reflect the change of UTC.

Also for the purpose of celestial navigation ephemeris, tables will need to take into account the fact that UTC will not approximate UT1 within 0.9 s.

6.6.3 Measures and time period required for maritime navigation to implement changes of UTC

IMO requests that the importance of the maritime systems is acknowledged in deciding on this item and attempt to minimize the impact on maritime services (IMO Document WRC15/13, 24 June 2015).

It will be necessary to consider the optimum way to discontinue the insertion of leap seconds in UTC. Some systems adapted to leap second insertion could be disrupted with the increasing offset UT1 – UTC. Time will be necessary to replace those systems at the user level, to avoid impact on navigation, a transition period of five to ten years should be provided.

6.7 Impact on Astronomy

Astronomical applications that use UTC to access UT1 would be impacted by a change of UTC. These include the pointing of telescopes, antennas, and instruments, and all software and procedures based on the current UTC. A change would also impact astronomers involved in providing astronomical data in almanacs and websites, where the current UTC is imbedded in the procedures and determination in the provided data.

The Earth orientation community is involved in providing observed and predicted values of the parameters required to describe the orientation of the Earth with respect to astronomical reference systems. These data are available from the internet via ntp, ftp, emails, and downloads. GPS, GLONASS, and BeiDou have begun broadcasting UT1-UTC and polar motion as well. Values of

UT1 to very good accuracy are thus available, although for many applications the current UTC is a sufficient representation of UT1.

6.7.1 Advantages and disadvantages of using the current UTC

The current UTC is satisfactory for users in the astronomical community that do not need very precise access to UT1, and can operate with offsets within the present tolerance. For those the broad and easy access to UTC/UT1 in its current form by different means represents an advantage as it provides easy access to low-accuracy UT1.

Users of UT1 to better than 0.9 s accuracy make use of the values of UT1 – UTC provided by the IERS and disseminated on the internet. Therefore, they are not affected by leap second insertions.

Since leap seconds are unpredictable and currently announced six months before their insertion, ephemerides for future dates over longer-time spans where UTC is the time argument involve predictions that could be erroneous if an unanticipated leap second event happened to occur between the date of the prediction and the date of the event.

6.7.2 Advantages and disadvantages of using a possible continuous UTC

Applications that currently use UTC as a low accuracy representation of UT1 and vice versa, will be compelled to define new strategies, new standards, update software, and educate users. This paradigm shift would represent a disadvantage to these groups. Astronomers are used to developing procedures and programs, thus intellectually this should not be an issue however on a practical level, considering staff effort, legacy software, this will involve some level of overhead. This also does not take into account non-experts that have software which assume that UTC and UT1 are used interchangeably.

Software developed for applications involving UT1 that use the values of UT1 – UTC provided by the IERS might fail if the value of UT1 - UTC exceeds 0.9 s, and consequently may need revision and changes.

Ephemerides and tables not involving topocentric coordinates, using for example TT, which is a continuous time scale, would not be affected by any change. Ephemerides expressed in UTC would benefit from the removal of the contribution to the error in the prediction of UT1 – UTC due to future leap seconds.

6.7.3 Measures and time period required for Astronomy to implement changes of UTC

Stopping the insertion of leap seconds in UTC will be feasible only after all users have had sufficient notice to access UT1 - UTC via NTP, ftp/https downloads, web services, or GNSS.

6.8 Impact on Geodesy

The topic of a possible redefinition of UTC has been extensively discussed during the last few years by this geodetic community, which pronounced in favour of stopping the insertion of leap seconds.

Nowadays processing of space geodetic measurements needs sub-second temporal resolution. In particular this one requires the computation of the rotation transformation between terrestrial and celestial reference frames, in particular the Earth rotation angle, namely UT1.

In 1 s the Earth rotates by about 15". So any application involving the Earth attitude with an accuracy less than 15", requires a temporal resolution smaller than 1 s. The present requirement for Earth attitude is an accuracy of 0.0001" and less, corresponding to a 7 μs temporal resolution that is the present uncertainty on UT1.

On the other hand, the Earth rotation angle is composed of a component increasing linearly with respect to continuous TT or TAI time scale, and an irregular part reflecting the Earth rotation changes and given by UT1 – TT or UT1 – TAI and provided by IERS at a daily sampling rate (actually UT1 – UTC).

6.8.1 Advantages and disadvantages of using the current UTC

With a sub-second temporal resolution, any user is confronted to the computation of the rotation angle in UTC time scale between the seconds 59 and 60 when a leap second occurs. It involves both the time linear part and the interpolation of sampled UT1 - UTC daily at the required instant. But this is impossible in the UTC discontinuous scale. Practically, the computation of the rotation angle is performed in TT or TAI, and the instant is labelled back in UTC.

Leap seconds have become an unnecessary complication and conspire against the encouragement to use the very good results of modern geodetic techniques. In terms of modern geodesy and modern telecommunication tools, the interest for continuing with leap second insertions in the UTC time scale appears to be more and more limited and obsolete.

6.8.2 Advantages and disadvantages of using a possible continuous UTC

Stopping leap-second insertion would lead to a simplified procedure for computing the Earth rotation angle, and avoid any substitution of the time scale.

Being continuous, UTC could be used for numerical integrations of the movement of bodies over long periods of time; moreover, there is easy access to the ephemeris of solar system bodies which have TT as argument, taking into account that the difference TT – UTC would become constant if leap seconds insertion is stopped.

6.8.3 Measures and time period required for Geodesy to implement changes of UTC

The measures and time period required to implement changes in UTC should be those requested by the various observation techniques contributing to Geodesy measurements.

6.9 Impact on radio sciences

Radio science research and applications need a unique and continuous reference time scale (see Annex 3). Many technological concerns associated with adapting systems and software can be solved, and the challenge can be justified in comparison to the scientific and operational benefits of a continuous time scale.

6.9.1 Advantages and disadvantages of using the current UTC

Leap second insertion has led to serious problems and breakdowns in contemporary applications that require a continuous time reference. In an attempt to minimize these problems, several actions have been put into practice by different users, either using a non-standard continuous time reference or adopting different non-standard procedures to synchronize to UT1. Due to the ambiguity in the date during the insertion of a leap second, the metrological traceability to UTC that is required by some users is frequently not realized.

There are various risks caused by the adjustment of leap seconds in UTC that are not predictable over the long term.

6.9.2 Advantages and disadvantages of using a possible continuous UTC

A unique and continuous time scale is essential for scientific research and related activities in radio sciences.

There are still concerns about unforeseeable effects caused by changing the current method of maintaining UTC to agree with UT1 within 0.9 s.

6.9.3 Measures and time period required for radio sciences to implement changes of UTC

The present limitation on the maximum value of UT1 – UTC should be withdrawn after a suitable period of public notice provided that real-time UT1 – UTC dissemination is achieved and that no currently unforeseen problem is identified before 2023.

6.10 Impact on Time metrology and traceability

Changing UTC to a continuous time scale will not require any particular modification in the process of calculation at the BIPM. It will not modify the process of realization of the local UTC(k) at the timing metrology laboratories; on the contrary, it will avoid the perturbations provoked by the insertion of a leap second at irregular intervals. As a benefit for users requiring metrological traceability to UTC, a continuous reference time scale will provide traceability to the SI second at any time; this is not possible with the present UTC, since the date ambiguity provoked at the insertion of a leap second does not assure metrological traceability.

6.11 Impact on IT and Industry 4.0

The following problem has significant effect on many segments of each individual economy. It is complicated by the lack of leap-second servicing standard, the poor dialogue between the IT and time metrology community, the diversity of implementation of GNSS receivers, as well as different approach of serving UTC between GLONASS vs GPS / GALILEO / BEIDOU / IRNSS.

Further continuation of handling *UTC leap second* introduces a high risk of failure for IT and OT. Although the leap-second problem has always existed, currently with exponentially growing automation and the close interdependence of entire Industry 4.0 systems, there is a need for urgent suspension of the *UTC leap-second*. Currently considered the first in history negative leap-second makes users especially worry.

The leap-second makes UTC time scale discontinuous, hence appearance of problems such as:

1) Time discrepancies in distributed system, where the validity of the data is determined by difference between *remote sensor timestamp* and receiving local timestamp of central server. This may lead to the acceptance of invalid data (wrongly computed DELAY) and, consequently, to the wrong predictive management. Such risk will increase with the growing popularity of TSN (Time Sensitive Networking) and TCC (autonomous Time Coordinated Computing) at Industry 4.0.

2) Failures of software and firmware of IoT devices based on the Windows or Linux/Unix kernels. It is to be noticed, that many modern IT / IoT devices produced as of today have firmware based on one of the operating systems listed above. The unexpected peaks in time introduced by the UTC leap second are dangerous for stability of the OS-kernel. They disturb the low-level event chronology, according to which concurrency management and the low-level utilization of system processes take place. Disturbing the chronology results in the "kernel panic" – risk causing crash of the operating system (OS), firmware or even a part of CLOUD.

The UTC leap second can trigger a large-scale domino effect, leading to a blackout: in telecommunication, power systems and Industry 4.0 automation. Sooner or later, such failures must begin to occur, unless a leap-second suspension remains effective. Considering very likely the upcoming of a negative leap second, which has never been put into practice before, it will be particularly very dangerous experiment on a working active production environment.

Further continuation of close monitoring of possible failures is necessary.

Related to the subject, a letter from industries with a petition has been addressed to the BR director (see Annex 4).

6.12 Impact on digital systems

6.12.1 Solutions to address the occurrence of a leap second in digital representations

A number of solutions have been implemented to address the occurrence of a leap second when time is represented as the number of seconds since some epoch. It has proven to be impossible to define a time scale that is simultaneously monotonic, smoothly varying, and traceable to UTC across a leap second, and different solutions, which emphasize different aspects of the requirements, have been deployed by various digital-time systems.

1) The Network Time Protocol (NTP) is very widely used to transmit time among digital systems on both local and wide area networks. The time stamp that is used in the NTP format expresses the UTC time as the number of seconds and fractions of a second that have elapsed since 1 January 1900. (This relationship is not supported in the messages that are exchanged in support of the protocol. It is implicitly assumed by all systems that use the protocol.) In the publicly supported version of the protocol, a leap second is realized by stopping the advance of the count of integer seconds for exactly 1 second at a value equivalent to 23:59:59 UTC on the day of a leap second. The fractional part of the second continues to advance at the normal rate, and rolls over to 0 after 0.9 s. Thus, 23:59:59.9 (the first time) is followed by 23:59:59.0 (the second time). The advance of the counter of integer seconds resumes when the seconds fraction rolls over to 0 a second time. Thus, the integer second portion of the time stamp following 23:59:59 the second time is equivalent to 00:00:00 of the next day.
2) A less-common variant of the NTP method stops the advance of the integer second at a value equivalent to 00:00:00 of the day after the leap second. The process is the same as in the preceding paragraph; the only difference is the time at which the advance of the integer seconds counter is stopped for 1 s. Although this method is similar to method 1, above, it adds the extra second to a different day. This is not compatible with the definition.
3) The system clock is completely stopped for 2 seconds when the integer second is 23:59:59. The system time does not advance normally, and is incremented by 1 µs every time the system receives a time request. The integer second counter is advanced to 00:00:00 of the next day at the end of the 2 s interval, and the fractional seconds is reset to 0 at that instant. This method implicitly depends on the assumption that the system time will not be queried more than 999 999 times in the 2 second interval. There is no explicit provision in the method if this limit is exceeded.
4) The integer second portion of the elapsed time since the origin of the binary count is stopped for 1 s when a leap second occurs. The UTC time equivalent to the origin is adjusted by 1 s every time a leap second occurs. The resulting time scale is monotonic and smoothly varying across the leap second and can be defined to agree with UTC for contemporary data but not for older data.

In addition to these discrete methods, there are three methods that amortize a leap second by adjusting the frequency of the clock.

1) The Google "smear" method amortizes the leap second by adjusting the effective frequency of the system clock for some period during the leap second day.
2) A variant of this method amortizes the leap second by adjusting the effective frequency of the system clock over some other period; on the day following the leap second or symmetrically both before and after the leap second.
3) The Microsoft proposal slows the frequency of the system clock by a factor of 2 at 23:59:59.0 on a leap-second day. The time advances at one-half of the normal rate, so that it takes two seconds for the clock to advance to 00:00:00 of the next day.

These three methods produce time scales that are monotonic, but the rate of advance of the system clock differs among them and all of them will have errors both in time and in frequency with respect to UTC in the vicinity of a leap second.

All of these methods produce time stamps that agree with UTC in general, but disagree with UTC during, or immediately after a leap second event. Methods one and two generate time stamps that can violate causality; in the first method, for example, 23:59:59.5 the first time, occurred before 23:59:59.2 the second time, although the time stamps imply that the opposite was true. The apparent elapsed time between these two events is a negative value, so that these methods can produce time stamps that violate causality. This ambiguity is not a negligible problem. For example, the NTP time servers operated by NIST receive approximately 1 000 000 requests per second for time in NTP format.

Method 3 produces time stamps that are monotonic but are not smoothly varying – the rate of incremental the fractional part of the time depends on the number of processes that are requesting the system time. Therefore, different implementations of method 3 will generally not even agree with each other.

Method 4 will have problems with historical events, since event times that cross a leap second will have different origin times.

The apparent frequency of the oscillator in the system clock, computed by taking the difference between two stamps assigned to consecutive 1 PPS signals received from an external frequency reference, will be in error with all of these methods. This introduces a significant error into methods that synchronize the system time by using a frequency-lock loop.

In addition to not agreeing with UTC time stamps during a leap second, these methods do not agree with each other. None of these methods is a universally-accepted standard and none transmit any ancillary information about how the leap second is handled, so that a user has no way of evaluating or verifying the accuracy of a particular source of time information. This is especially problematic with the methods that amortize a leap second by a frequency adjustment over some interval. The interval is not defined in any standard, so that different implementations of this method may not agree with each other.

6.12.2 Summary of the impact on digital systems

The impact on digital systems of the current UTC with leap second adjustments is negative in all aspects. Any detailed consideration on the advantages / disadvantages of the present and potential future time reference is useless.

The impact of the present UTC can be summarized as follows:

A number of methods are in use to address the various problems associated with the occurrence of a leap second in UTC. All of these methods have a time error of order ±0.5 s in the vicinity of a leap second event, although they are compatible with UTC at other times. In addition, these methods do not agree with each other in the vicinity of a leap second.

In general, systems that implement these methods do not provide any information about which method is being used. Some versions of popular operating systems support multiple methods and the actual method that is used is chosen by the operator during the configuration of the system. Therefore, there is no way for a user to know which method is being used.

The number of methods that are currently used in digital systems to deal with leap seconds is increasing, and the proliferation of time scales that are not compatible with UTC or with each other is very undesirable. It greatly complicates digital time keeping and undermines the universal nature of UTC. This issue is not going to go away; it will almost certainly get worse with time given the continuance of the present leap second procedure. For example, the number of systems that use various versions of the Google “smear” method is increasing, even though this method is not compatible with UTC and will not satisfy the regulatory requirements for time stamps that are used in commercial and financial transactions.

6.13 Impact on the time-stamping service

The current TSS systems cannot support leap second adjustments due to the limitations of computer systems. The TSS systems must be taken out of service several hours before and after the occasional leap second adjustment. If the UTC procedure changes in the way that the insertion of leap seconds is stopped, the TSS systems will not need to be updated or changed.

6.13.1 Advantages and disadvantages of using the current UTC

There is no advantage of using the current UTC in a TSS.

A disadvantage associated with the usage of the current UTC is that the TSS systems must be taken out of service several hours before and after the occasional leap second adjustment.

The TSS systems not only rely on the traceability of a time stamp token (TST) to UTC, but also on a support system for monitoring and auditing the time of the entire system. Most of these systems are configured by computers and are required to operate with synchronized times. In the current UTC, however, leap second adjustments are performed on discrete 1 second steps and cannot be supported by conventional computer systems. Before and after a leap-second adjustment is implemented, the time-stamping service needs to be suspended for several hours to prevent malfunctions and to make sure that the whole system is synchronized when the service resumes. This is a source of reduced service reliability and operational risk. The impact is more significant when such suspension occurs during regular business hours, particularly in regions of the Asian and Pacific time zones.

6.13.2 Advantages and disadvantages of using a possible continuous UTC

The advantage of stopping the insertion of leap seconds in UTC is that it eliminates additional software and protocols to coordinate the accommodation of leap seconds in the systems. There are no problems without any modifications to the current TSS systems. This is because continuous time scale is a normal operating environment and there are no factors that cause trouble. This allows the TSS systems to always create a TST without interrupting service, thus improving TSS reliability of the TSS.

The TSS systems do not require access to UT1 and suppressing the leap second adjustments eliminates irregular operations in the systems. In consequence, there is no disadvantage of using a continuous UTC in the TSS.

6.13.3 Measures and time period required for time-stamping service to implement changes of UTC

No transition time is required for the TSS, simply because it consists of eliminating the irregular operations necessary to overcome the leap second adjustment in the TSS system. Continuous time is a normal operating environment, there is no need to change the current TSS systems.

6.14 Impact on financial services

Financial services rely on time stamping systems for the time tagging of their operations, and in consequence are equally impacted by leap second insertions. (See § 6.13.)

6.14.1 Advantages and disadvantages of using the current UTC

See § 6.13.1.

6.14.2 Advantages and disadvantages of using a possible continuous UTC

See § 6.13.2.

6.14.3 Measures and time period required for financial services to implement changes of UTC

The duration of the required transition time for those affected TSS systems is estimated to be less than one year. This is because it can be realized by suppressing the irregular operations due to the leap second adjustment in the TSS system.

6.15 Impact of a continuous international reference for time on the IERS and EOP users

6.15.1 Impact of a continuous international reference for time on the IERS

If a continuous time scale was established, the need for leap seconds would be eliminated. This would allow the value of UT1 – UTC to grow unbounded, which would have the following impacts on the IERS.

1) The format of any IERS data set containing UT1 – UTC would need to be changed to account for an increased number of digits to the left of the decimal place instead of the single digit that is currently in place.
   a) Note that the format for TAI – UT1 would not need modification because it already assumes an arbitrarily large number left of the decimal place.
2) There may be an increased interest in longer-term predictions, particularly of UT1 – UTC. This would necessitate research efforts into different algorithms for long-term predictions and may necessitate the creation of additional data sets.

In general, the change to a continuous international reference for time should have a minimal impact on the IERS or the way in which products are delivered.

6.15.2 Impact of a continuous international reference for Time on EOP Users

The IERS does not track the users of its products and so it is not possible to provide a definitive answer to the level to which a change to a continuous international reference time would impact IERS users. At a minimum, IERS EOP users would need to account for changes in the format of EOP data sets (see above) and the potential size of the UT1 – UTC. However, there are two circumstances that should mitigate the negative impact of changes to the definition of a reference time scale.

1) Institutions (e.g. the U.S. National Institute of Standards and Technology) have already established the dissemination of UT1 – UTC through network time protocol (NTP). This functionality could be substituted seamlessly for projects that already use NTP-delivered UTC as a proxy for UT1 estimation. The change in operational configuration should be minimal and the result would be improved UT1 values inserted into operational systems.
2) Some GNSS (e.g. the Global Positioning System (GPS)) will broadcast the EOPs that they are using to perform the celestial reference frame to terrestrial reference frame transformation. This capability could be substituted seamlessly for projects that already use GNSS-delivered UTC as a proxy for UT1 estimation. The change in operational configuration should be minimal and the result would be improved UT1 values inserted into operational systems.

These two data dissemination methods are in addition to the traditional EOP delivery methods discussed above.

6.16 Impact on other applications

Other than technical considerations in user systems the societal impact and alternative solutions need to be discussed and considered. Stopping the insertion of leap seconds in UTC could be interpreted as a break of the relation of UTC to time measured by the rotation of the Earth with respect to the Sun. Twenty-seven seconds have been inserted in UTC up to 2022 to limit its difference with UT1. However, UTC which is meant to be a close approximation to mean solar time can vary by up to sixteen minutes from apparent solar time, which is the time as measured by the rotation of the Earth with respect to the actual Sun. In addition, civil time in most locations in the world is adjusted from solar time by time zones and “daylight saving” regulations in some cases, leading to civil time many hours different from local solar time. This brings into question any argument asserting a negative impact on society of a civil time derived from any time scale without leap seconds. The conceptual relation of UTC with the Earth’s Rotation Angle (represented as UT1) will not be lost by any modification of the value of the tolerance of their offset.

7 Conclusion / Summary of relevant issues considered in this Report

This Report is motivated by the statements of Resolution **655 (WRC-15),** and responds to its *resolves to invite the ITU Radiocommunication Sector* 1 to 4 trying to answer the three pertinent questions in Question ITU-R 236-2/7 (2017) with the input of most relevant organizations:

1) What are the various aspects of current and potential future reference time scales, including their impacts and applications in telecommunications, industry, and other areas of human activity?

2) What are the requirements for the content and structure of time signals to be disseminated by radiocommunication systems?

3) Does the current leap second procedure satisfy user needs or should an alternative procedure be adopted?

The complexities of defining a time scale for universal application requires a body of expertise comprised of specialists in the subject. The responsibilities and expertise of the different international organizations involved in determining the international reference time scale have been taken into account.

The determination of how the international reference time scale relates to other time sources, including UT1, falls under the authority of the BIPM in conjunction with the CCTF, CIPM and CGPM; however, the emissions and the dissemination of standard-frequency and time-signals, including time scale offsets, reside within the authority of the ITU-R.

The CGPM in its Resolution 2 (2018) “On the definition of time scales” recommends “to consider the present limitation on the maximum magnitude of UT1 – UTC so as to meet the needs of the current and future user communities”. Work has already started in this direction at the BIPM and the CCTF that has led to a consensus towards a continuous reference time scale. This is reported in the Document 7A/43 and the relevant draft resolution has been submitted for adoption by the CGPM 2022.

In line with Resolution **655 (WRC-15)**, the relationship between the ITU-R and the BIPM has been strengthened, notably with a regular and intensified participation between experts in both the ITU-R and CCTF meetings, and also through the signing in 2020 of a Memorandum of Understanding (MoU ITU BIPM 2020).

The ITU-R has considered the advantages and disadvantages of the current UTC from many different perspectives, and this Report outlines these points in detail.

The following observations were made during the work on this Report and are summarized here:

A reference time scale should:

– allow the identification of events in time with monotonic, unambiguous time stamps;

– represent also a reference for the time unit and for clock rate (frequency), over very long periods (i.e. a few hundred years);

– have a known relation with the rotation of the Earth, and that its offset from UT1 is well known and disseminated, since for a number of users the information on the offset UT1 – UTC is mandatory.

The practice of maintaining UTC in close approximation to mean solar time by introducing leap seconds was decided in the early 1970s in view of the needs of celestial navigation which was then still common in civil marine activities. With the advent of GNSS these needs have vanished. The current practice continues to violate the first two basic requirements above.

A possible solution of these issues is the relaxation of the tolerance within which UTC and UT1 are maintained. Already today the offset between UTC as basis of civil time and local solar time vary throughout the year by about ±15 minutes and in addition civil time is governed by adherence to time zones that are often only loosely related with solar time at the respective geographical longitude. In consequence, the perception of "time" by the common people will not change.

In this case, additional constraints should be considered, taking into account the importance of many aspects of critical national infrastructures:

– Actions are needed to address the backward compatibility issue and updating/replacing existing equipment is required in some cases when backward compatibility cannot be ensured.

– Some user groups would like to see the stop of leap seconds as soon as possible. Other users have asked for a transition period, between the decision and its implementation, to update their systems and procedures; the maximum of 15 years is requested.

When these requirements are fulfilled, the reference time scale will serve the largest number of user communities in civil life and in scientific applications.

In case of these changes, UTC remains the only international reference time scale. Reasons for not considering TAI or any GNSS system time as potential candidates are developed in this report.

The definition of UTC (CGPM, Resolution 2 (2018)) remains unchanged.

It can be concluded that if the decision on a continuous reference time scale will be taken, remaining work, e.g. cooperation between ITU-R and international organisations, and necessary updates of Recommendation ITU-R TF.460, falls as general task under the responsibility of the relevant ITU-R working groups.

During the discussions and the work leading to this report, several questions have been considered and are reported in Table 7.1 to help the reader in understanding some of the most relevant issues.

TABLE 7.1

Question	Answer
1 Is it necessary and useful to change the current mechanism to correct UTC by leap seconds to maintain a close agreement with UT1?	For a number of users, this is really useful, because it allows to get rid of the irregular introduction of leap seconds and get a continuous reference time scale (at least for a long time). Most of the users involved in applications evaluated in this Report stated various levels of benefits from transitioning to a continuous time scale. Technological concerns associated with adapting systems and software can be solved, and the challenge can be justified in comparison to the scientific and operational benefits of a continuous time scale.
2 What are the main advantages and disadvantages of a continuous UTC?	The main advantages include: – Avoiding the risk of failure in the critical national infrastructure relying on synchronization due to: a) the irregular introduction of leap seconds; b) the proliferation of ad hoc methods that have been developed as alternatives to the introduction of the leap second. – Simplifying operations of industrial, scientific, and commercial applications. – Recognizing UTC as the only international time scale by all operators and in all applications, and reducing the risk of using multiple reference time scales not based on international collaboration. – Avoiding the risk of a possible negative leap second due to the recent Earth rotation acceleration. This has never been tested and not even implemented in some system. The main disadvantages include: – Increasing the value of the offset UT1 - UTC makes the correction of UTC a rare event (more than 100 years). In the event of a large correction in the future potential risks of failure exist. A detailed procedure and the necessary preventive education, many years in advance, will be of the utmost importance. – Updating/replacing existing equipment is required in some cases when backward compatibility cannot be ensured. – Adapting documentation and data formats to the new maximum value of UT1 - UTC. – Updating software and operational procedures for the systems that use UTC as a low accuracy approximation of UT1.
3 How will the continuous time scale relate to UT1 and what format would be recommended for time signal emissions?	In case of continuous time scale, the difference between UTC and UT1 will increase. For a number of users the information on the offset UT1 – UTC is mandatory. So it is necessary to provide that information with appropriate transmission and distribution of standard frequency and time signals. The IERS will continue the permanent monitoring of UT1 and plans to increase the dissemination of UT1 – UTC. No discussion has been made yet on the format of the time signal emission with UT1 – UTC exceeding the value of 0.9 s. This will be the scope of the future work of the ITU in consultation with the BIPM and related international organizations and industrial groups.

TABLE 7.1 (*continued*)

Question	Answer
4 Which are the intermediate steps leading to a continuous UTC?	For the BIPM, in consultation with ITU and other relevant international organizations: – Define the new extended value on the offset UT1 – UTC and all necessary intermediate steps including the application date, the application procedure, a possible periodic revision of this choice. For the ITU in consultation with the BIPM and related international organizations and industrial groups: – Update the documents including information on the offset UT1 – UTC, and the Recommendation ITU-R TF.460-6 including the procedure for the leap second and the possible changes in format of the code for transmitting DUT1. For Member States and Sector Members: – Identify and educate the existing communities of users. – Determine the necessary updates/replacements in the equipment in order to deal with UT1-UTC larger than 0.9 s.-when necessary, carry out the modification/replacement of the equipment.- Update the rules for certification of equipment and related documentation. – Update of legal documentation. For all: – Carry on an extended education and information campaigns.
5 How long will it take for the transition to a continuous UTC?	Some user groups would like to see the stop of leap seconds as soon as possible; these include: – power grids; – telecom; – IT; – financial sector; – space agencies. Other users have asked for a transition period, between the decision and its implementation, to update their systems: – astronomers may require some years – maritime navigation indicated 5 to 10 years – maritime mobile, aeronautical and radiodetermination services, indicated not less than 10 years – the RNSS GLONASS requested a transition period of at least 15 years – fixed-satellite, broadcasting-satellite, and mobile-satellite services did not indicate the transition period, which could be as long as operational lifetime of the systems.
6 Which will be the new tolerance on the value of |UT1 – UTC|?	Currently there is no decision, but the new maximum value of the offset UT1 – UTC should allow at least one century without correction. For example, if the current evolution of the difference continues, a two-digit integer number of seconds may cover a few hundred years. The exact value will be considered during further discussions by the BIPM, the ITU-R, and the other relevant international organizations.
7. Would the transition towards a continuous UTC change the definition of Coordinated Universal Time (UTC)?	The definition of UTC confirmed by the CGPM Resolution 2 (2018) will remain unchanged. The term UTC will remain in use. It will be necessary to revise Rec. ITU-R TF.460-6 accordingly.

TABLE 7.1 (*end*)

Question	Answer
8 What changes to the ITU-R documentation (Radio Regulations, Resolutions, Recommendations) will be required in case of continuous UTC?	Provision No. **1.14** of Article **1** in the Radio Regulations will need to be updated to specify the correct link to the corresponding Resolution on the description of UTC. Recommendation ITU-R TF.460-6 has to be updated. There is a view that the current DUT1 transmission scheme as in Rec. ITU-R TF.460-6 is going to become obsolete and services that currently transmit DUT1 need to change the format. Documentation of services will need to be updated. Most ITU-R documents referring to UTC need no change as they do not explicitly refer to the leap second insertion. Resolution **655 (WRC-15)** will need to be updated to report the decision reached on the UTC issue.
9 What measures are needed to ensure the backward compatibility if a decision of a continuous UTC is made?	Enough time will be given for equipment upgrade and modification, taking into consideration the applications needing long transition periods. Also see the answers to questions 4 and 5.

8 References

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Annex 1

CGPM Resolution 2 (2018)

On the definition of time scales

The General Conference on Weights and Measures (CGPM), at its 26th meeting,

considering that

– Resolution 1 adopted by the CGPM at its 14th meeting (1971) requested the CIPM to define International Atomic Time (TAI),

– no complete self-contained definition of TAI has been provided officially by the CIPM,

– the Consultative Committee for the Definition of the Second (CCDS) proposed in its Recommendation S2 (1970) a definition which was extended by a Declaration of the CCDS in 1980,

– the CGPM at its 15th meeting (1975) noted that Coordinated Universal Time (UTC), derived from TAI, provides the basis of civil time, and strongly endorsed this usage,

recognizing that

– the mission of the BIPM is to ensure and promote the global comparability of measurements, including the provision of a coherent international system of units,

– the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) with the International Association of Geodesy (IAG) are responsible for defining reference systems for Earth and space applications,

– the International Telecommunication Union Radiocommunication Sector (ITU-R) is responsible for coordinating the dissemination of time and frequency signals and making relevant recommendations,

– the International Earth Rotation and Reference Systems Service (IERS), a service of the IAU and IUGG, is responsible for providing information required to relate terrestrial and celestial reference systems, including time-varying measurements of the Earth's rotation angle, UT1 - UTC, the low-precision prediction of UT1 - UTC for time signal broadcasts, DUT1, and for deciding and announcing leap second insertions,

noting that

– Resolution A4 (1991) of the IAU defined, in Recommendations I and II, the Geocentric Reference System as a system of space-time coordinates for the Earth within the framework of general relativity, and, in Recommendation III, named the time coordinate of that reference system "Geocentric Coordinate Time" (TCG),

– Resolution A4 (1991) of the IAU further defined, in Recommendation IV, Terrestrial Time (TT) as another time coordinate in the Geocentric Reference System, differing from TCG by a constant rate; the unit of measurement of TT being chosen to agree with the SI second on the geoid,

– Resolution B1.9 (2000) of the IAU redefined TT to be a time scale differing from TCG by a constant rate: $d\mathrm{TT}/d\mathrm{TCG} = 1 - L_G$, where $L_G = 6.969290134 \times 10^{-10}$ is a defining constant (the numerical value of L_G was chosen to conform to the value $W_0 = 62636856.0\ \mathrm{m^2s^{-2}}$ for the gravity potential on the geoid as recommended by Special Commission 3 of the IAG in 1999),

– the redefinition of TT in 2000 introduced an ambiguity between TT and TAI as the CCDS had stated in 1980 that TAI was to have "*the SI second as realized on the rotating geoid as the scale unit*" while the definition of TT does not refer to the geoid,

states that

– TAI is a continuous time scale produced by the BIPM based on the best realizations of the SI second, and is a realization of TT as defined by IAU Resolution B1.9 (2000),

– in the transformation from the proper time of a clock to TAI, the relativistic rate shift is computed with respect to the conventionally adopted equipotential $W_0 = 62636856.0\ \mathrm{m^2s^{-2}}$ of the Earth's gravity potential, which conforms to the constant L_G defining the rate of TT,

– as stated in the IAU Resolution A4 (1991), TT - TAI = 32.184 s exactly at 1 January 1977, 0h TAI at the geocentre, in order to ensure continuity of TT with Ephemeris Time,

– UTC produced by the BIPM, based on TAI, is the only recommended time scale for international reference and the basis of civil time in most countries,

– UTC differs from TAI only by an integral number of seconds as published by the BIPM,

– users can derive the rotation angle of the Earth by applying to UTC the observed or predicted values of UT1 - UTC, as provided by the IERS,

– UTC provides a means to measure time intervals and to disseminate the standard of frequency during intervals in which leap seconds do not occur,

– traceability to UTC is obtained through local real-time realizations "UTC(*k*)" maintained by laboratories contributing data to the calculation of UTC, identified by "*k*",

confirms that

1 International Atomic Time (TAI) is a continuous time scale produced by the BIPM based on the best realizations of the SI second. TAI is a realization of Terrestrial Time (TT) with the same rate as that of TT, as defined by the IAU Resolution B1.9 (2000),

2 Coordinated Universal Time (UTC) is a time scale produced by the BIPM with the same rate as TAI, but differing from TAI only by an integral number of seconds,

and **recommends** that

– all relevant unions and organizations consider these definitions and work together to develop a common understanding on reference time scales, their realization and dissemination with a view to consider the present limitation on the maximum magnitude of UT1 - UTC so as to meet the needs of the current and future user communities,

– all relevant unions and organizations work together to improve further the accuracy of the prediction of UT1 - UTC and the method for its dissemination to satisfy the future requirements of users.

Annex 2

Response of IERS to WRC-15

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English only

International Earth Rotation and Reference Systems Service (IERS)

RESPONSE TO WRC

Background

The International Earth Rotation and Reference Systems Service (IERS) was established in 1987 by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG). The primary objectives of the IERS are to serve the astronomical, geodetic and geophysical communities by providing the following:

– The International Celestial Reference System (ICRS) and its realization, the International Celestial Reference Frame (ICRF);

– The International Terrestrial Reference System (ITRS) and its realization, the International Terrestrial Reference Frame (ITRF);

– Earth orientation parameters (EOPs) required to study Earth orientation variations and to transform between the ICRF and the ITRF;

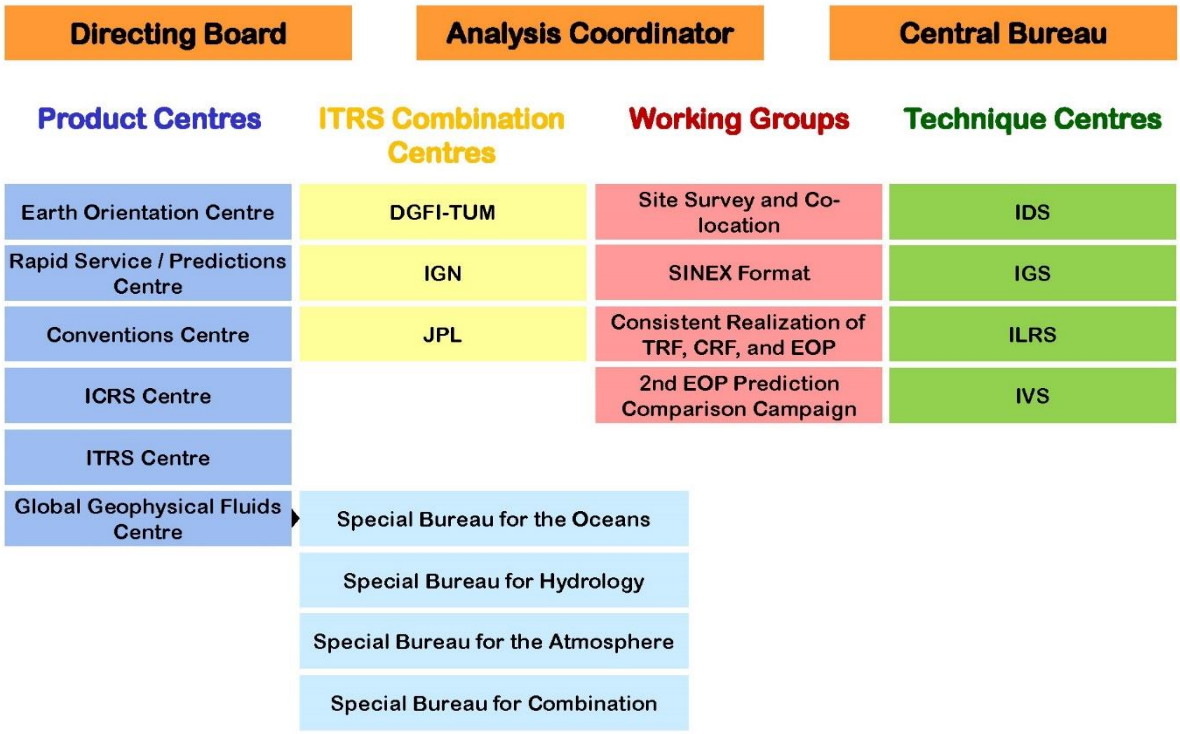
– Geophysical data to interpret time/space variations in the ICRF, ITRF or Earth orientation parameters, and model such variations;

– Standards, constants and models (i.e. conventions) encouraging international adherence.

The way in which the IERS is organized is shown below in Figure 1.

FIGURE 1

The Structure of the IERS



Earth orientation parameters

Earth orientation parameters (EOPs) are the numbers that define the relationship between the International Terrestrial Reference Frame (ITRF) and the International Celestial Reference Frame (ICRF). EOPs are comprised of three general motions with a total of five parameters: two polar motion components (PM-x, PM-y), the variable Earth rotation component (UT1), and corrections to the two celestial pole coordinates (dX, dY).

EOPs display a high level of variability due to a number of causes. Over periods of less than a couple of years, weather, oceans, and hydrology play a dominant role in the variations of Earth orientation. The mechanisms responsible for these variations are both a time-dependent distribution of mass (both water and air) as well as the change of angular momentum (again due to both water and air) to the solid Earth. Longer-term variations are generally caused by geophysical phenomena as well as by the gravity of the Moon and the Sun. As can be intuited, the effects of the forces causing changes to EOPs are highly variable and highly unpredictable. Even using the best atmospheric, oceanic and other Earth angular momentum observations and models, positive skill in predictions is only obtained out to a few weeks. Beyond that, some combination of deterministic and stochastic predictions are necessary to provide long-range EOP estimates.

EOPs have several practical purposes and are therefore used by many operational systems. EOPs are necessary inputs for modern day navigation systems such as global navigation satellite systems (GNSS). They are also necessary for pointing ground-based detectors or antennas toward the correct part of the sky and they are necessary for pointing communication satellites toward the correct spot on the Earth. Because of these practical and real-time needs, many operational EOP users are more interested in EOP predictions than they are in after-the-fact EOP determinations.

Earth rotation determination

The variable Earth's rotation, UT1, can be determined by making careful ground-based observations of celestial objects. Very long baseline interferometry (VLBI) is used extensively because VLBI is the only technique that is capable of determining UT1 directly. Other techniques such as global navigation satellite systems (GNSS), satellite laser ranging (SLR), lunar laser ranging (LLR), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) can only determine parameters related to UT1, but cannot determine UT1 directly. By combining the measurements from techniques such as the VLBI, GNSS, SLR, LLR, and DORIS, it is possible to create a more accurate and more robust determination of all Earth orientation parameters, including UT1.

The IERS has two Centers that are responsible for providing EOPs to users. The Earth Orientation Centre (EOC), located at the *Observatoire de Paris*, is responsible for monitoring the long-term Earth orientation parameters, publication for time dissemination and the leap second announcements. The Rapid Service/Prediction Centre, located at the U.S. Naval Observatory, is responsible for providing orientation parameters on a rapid turnaround basis, primarily for real-time users and others needing the highest-quality EOP information sooner than that available in the final series published by the IERS EOC.

IERS Earth orientation parameter products

The IERS has created different EOP products in order to meet the needs of a variety of users, in the form of Bulletins and files with continuous series. Below is a brief summary of the IERS Bulletins:

– IERS Bulletin A – Contains rapid determinations for Earth orientation parameters;

– IERS Bulletin B – Contains monthly Earth orientation parameters;

– IERS Bulletin C – Contains announcements of the leap seconds in Coordinated Universal Time (UTC);

– IERS Bulletin D – Contains announcements of the value of DUT1.

Continuous series include several 'finals' series by the Rapid Service/Prediction Centre and the C04 series by the Earth Orientation Centre.

The dissemination methods for IERS products include hypertext transfer protocol (http) and file transfer protocol (ftp). See https://www.iers.org/EOP for a list of IERS EOP products.

Relation between UT1 and UTC

Historically, UTC has been constrained to be sufficiently close to UT1. To ensure this, leap seconds were inserted into UTC so that the difference |UT1 – UTC| < 0.9 s. The insertion of a leap second maintains the value of UT1 – UTC below the 0.9 s tolerance. A positive or negative leap second should be the last second of a UTC month, but first preference should be given to the end of December and June, and second preference to the end of March and September. Since 1972 there have been 27 leap seconds.

The IERS, as the organization responsible for providing EOPs, was given the responsibility by the International Telecommunications Union (ITU) to determine the occurrence of leap seconds. The IERS must provide notification of impending leap seconds at least two months in advance although typically six-months' notice has been provided. Due to the variability of the Earth's rotation it is difficult to predict the occurrence of the next leap second more than six months in advance.

Impact of a continuous international reference for time on the IERS

If a continuous time scale was established, the need for leap seconds would be eliminated. This would allow the value of UT1 – UTC to grow unbounded, which would have the following impacts on the IERS.

1) The format of any IERS data set containing UT1 – UTC would need to be changed to account for an increased number of digits to the left of the decimal place instead of the single digit that is currently in place.

a) Note that the format for TAI – UT1 would not need modification because it already assumes an arbitrarily large number left of the decimal place.

2) There will be conventional routines that will need to be modified to account for any assumptions that the difference between UT1 and UTC will be sufficiently small (e.g. solid earth tide models). However, these are issues that can be addressed well in advance of any change to a continuous time scale.

3) There will be an increased interest in UT1 – UTC, especially for applications that used UTC as a proxy for UT1. IERS have to make UT1 – UTC more easily available, e.g. in the form of a web service.

4) There may be an increased interest in longer-term predictions, particularly of UT1 – UTC. This would necessitate research efforts into different algorithms for long-term predictions and may necessitate the creation of additional data sets.

In general, the change to a continuous international reference for time should have a minimal impact on the IERS or the way in which we deliver our products.

Impact of a continuous international reference for time on EOP users

The IERS does not track the users of our products and so it is not possible to provide a definitive answer to the level to which a change to a continuous international reference time would impact IERS users. At a minimum, IERS EOP users would need to account for changes in the format of EOP data sets (see above) and the potential size of the UT1 – UTC. However, there are two circumstances that should mitigate the negative impact of changes to the definition of a reference time scale.

1) Institutions (e.g. the U.S. National Institute of Standards and Technology) have already established the dissemination of UT1 – UTC through network time protocol (NTP). This functionality could be substituted seamlessly for projects that already use NTP-delivered UTC as a proxy for UT1 estimation. The change in operational configuration should be minimal and the result would be improved UT1 values inserted into operational systems.

2) Some global navigation satellite systems (GNSS) (e.g. the Global Positioning System (GPS)) will broadcast the EOPs that they are using to perform the celestial reference frame to terrestrial reference frame transformation. This capability could be substituted seamlessly for projects that already use GNSS-delivered UTC as a proxy for UT1 estimation. The change in operational configuration should be minimal and the result would be improved UT1 values inserted into operational systems.

These two data dissemination methods are in addition to the traditional EOP delivery methods discussed above.

Prepared by Brian J. Luzum

with contributions by Wolfgang R. Dick, Richard S. Gross, Erricos C. Pavlis, and Nicholas G. Stamatakos

12 April 2021

Annex 3

U.1. Resolution on the need for a continuous reference time scale (2021)

The URSI Council,

considering that

a) the current practice of maintaining the Coordinated Universal Time (UTC) within 0.9 s of the Earth's rotation angle (UT1) by occasional leap second adjustments has been under discussion since the late 1990s;

b) the Radiocommunication Sector of the International Telecommunication Union (ITU-R) discussed the realization of time scales and dissemination of time signals via radiocommunication systems during its World Radio Conference 2015 (WRC-15) and resolved in Resolution 655 to further and more widely study the various aspects of current and potential future reference time scales, including their impacts and applications, in cooperation with URSI and other relevant international organizations;

c) in 2018 the 26th General Conference of Weights and Measures (CGPM) formally confirmed in its Resolution 2 the definitions of International Atomic Time (TAI) and Coordinated Universal Time (UTC), and asked all relevant scientific unions and organizations to work together to develop a common understanding on reference time scales and their realization and dissemination, with a view to considering the present limitation on the maximum magnitude of UT1 - UTC so as to meet the needs of the current and future user communities;

d) URSI Commission A organized a wider consultation with experts from various fields to request their opinions on the adoption of a continuous reference time scale,

noting that

a) the insertion of leap seconds has led to serious problems and breakdowns in contemporary applications, such as satellite navigation, distributed measurement systems, and computer networks, that require a continuous time reference;

b) in an attempt to minimize these problems, several actions have been put into practice by different users, either using a non-standard continuous time reference (i.e., GPS time), or adopting different procedures to synchronize to UT1;

c) these actions have in turn caused confusion and errors for the users;

d) due to ambiguity during the insertion of a leap second, the metrological traceability to UTC that is required by some users is frequently not realized;

e) there are still concerns about unforeseeable effects caused by changing the current method of maintaining UTC to agree with UT1 within 0.9 s;

f) UT1 is necessary for applications in the space industry, Earth-based observations, for transformation between fixed and rotating reference systems, and for these applications realtime UT1 signal dissemination is needed;

g) the definitive values of UT1 – UTC are provided by the International Earth Rotation and Reference Systems Service (IERS) on the internet, and are also available via other time dissemination techniques by radio signals, Global Navigation Satellite Systems, and Internet time protocols;

h) TAI should not be considered as an option to achieve a continuous reference time scale since in its present form it provides only a frequency reference and is not disseminated by clocks, *recognizing that*

a) URSI passed the URSI Resolution of Strengthening the URSI and ITU relationship in its General Assembly in Lille, 1996, and resolved that the board shall work with ITU in the identification of topic areas of mutual concern, and prepare URSI statements on such topics in an appropriate form;

b) an URSI-wide working group was formed in 2002 and the risks that the occasional leap-second adjustments might cause were identified;

c) Commission A (Electromagnetic Metrology) of URSI expressed its opinion in 1999 that the procedure of leap-second insertions should be stopped and thus UTC should become a continuous reference time scale, and that this position was confirmed in 2014 by a Resolution of Commission A,

resolves for URSI to make the following statements:

1 All Global Navigation Satellite Systems are requested to consider broadcasting UT1 – UTC to a precision of a millisecond or better, within the constraints of their available funding and development latencies. In addition, systems providing UT1 – UTC over the Internet should be hardened against cyber-attacks and should be supplemented with additional secondary sources for users who only require annual knowledge of UT1 – UTC;

2 There are various risks caused by the adjustment of leap seconds on UTC that are not predictable over the long term;

3 A unique and continuous reference time scale is essential for scientific research and related activities in Radio Science;

4 Many of the technological concerns associated with adapting systems and software can be solved, and that challenge can be justified in comparison to the scientific and operational benefits of a continuous reference time scale;

5 Therefore, the present limitation on the maximum magnitude of UT1 – UTC should be withdrawn after a suitable period of public notice provided that real-time UT1 – UTC dissemination is achieved and that no currently unforeseen problem is identified before 2023.

Annex 4

Letter addressed from industries to the BR Director accompanying a petition to consider the discontinuation of the insertion of leap seconds in UTC. The petition itself is not included since it contains personal data

Date: 30th of January 2022

To
Director, ITU Radiocommunication Bureau
Mr. Mario Maniewicz

Dear Mr. Maniewicz,

On behalf of the ITSF (The International Timing & Sync Forum) group of sponsors and exhibitors, and the OCP-TAP (The Open Computing Project – Time Appliances Project), we are sending attached signed petition addressed to ITU Radiocommmunication, with a question to consider discontinuation of the *UTC leap seconds*.

The International Timing and Sync Forum (ITSF) sponsors and exhibitors signed on petition represents over 90% of global market of manufactures of commercial time & frequency appliances, test and measurement equipment.

The The Open Computing Project – Time Appliances Project (OCP-TAP) is newly operating since 2020, a group of timing experts related to cloud computing and IT industry. The OCP has been funded by Facebook and groups trade names: Google, Amazon, Microsoft, NVIDA, Intel, Oracle, CISCO, IBM etc. The OCP-TAP handles open hardware repository of synchronization hardware, important for state of the art CLOUD, FOG, EDGE computing.

We, the commercial timing community, deeply understand that, the further continuation of handling *UTC leap second* introduces a high risk of failure for modern IT and Industry4.0 (OT). Although the leap-second problem has always existed, currently with exponentially growing automation and the close interdependence of entire Industry4.0 systems, there is recommendation for immediate suspension of the *UTC leap-second*. Currently considered the first in history negative UTC leap-second makes us especially worry.

The attached petition was signed during the ITFS2021 conference Brighton UK (November 2021), by a major group of exhibitors and sponsors. The OCP-TAP and Facebook ware main speakers during this conference.

Best regards,

Tomasz Widomski
in behalf of ITSF group of sponsors

Ahmad Byagowi
in behalf of OCP-TAP project

Attn:
The Petition , singed by the group of ITSF2021sponsors and OCP-TAP leader

Copy to attention of:
Mr. Joseph Achkar (Chair, ITU-R WP-7A)

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